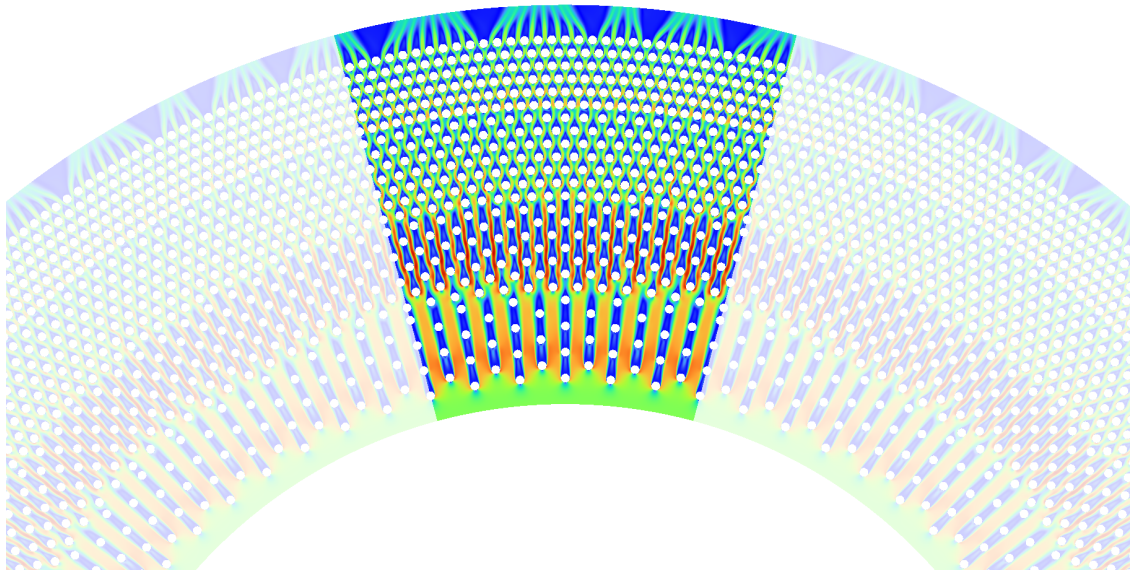




CHALMERS
UNIVERSITY OF TECHNOLOGY



Automation and Evaluation of Radial Flow Heat Exchangers in 2D

Master's thesis in Mechanics and Maritime sciences

Jay Baviskar, Yasser Alrifai

Mechanics and Maritime sciences

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

MASTER'S THESIS 2024

Automation and Evaluation of Radial Flow Heat Exchangers in 2D

Jay Baviskar, Yasser Alrifai



CHALMERS
UNIVERSITY OF TECHNOLOGY

Mechanics and Maritime sciences
Division of Fluid Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024

Automation and Evaluation of
Radial Flow Heat Exchangers in 2D
Jay Baviskar, Yasser Alrifai

© Jay Baviskar, Yasser Alrifai, 2024.

Supervisor: Michal Nitulescu, GKN Aerospace AB
Examiner: Carlos Xisto, Department of Fluid Mechanics

Master's Thesis 2024
Mechanics and Maritime sciences
Division of Fluid Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Typeset in L^AT_EX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2024

Automation and Evaluation of Radial Flow Heat Exchangers in 2D
Jay Baviskar, Yasser Alrifai
Mechanics and Maritime sciences
Chalmers University of Technology

Abstract

This study explores the automation and evaluation of radial flow heat exchangers in a two-dimensional (2D) setting using Computational Fluid Dynamics (CFD). Radial flow heat exchangers are widely being recognized to play a crucial role in the aerospace industry. The research examines how different tube arrangements within the heat exchangers impact heat transfer, pressure drop, and overall performance. A script was developed to automate the entire CFD workflow, streamlining the process of conducting simulations on different tube configurations and facilitating performance analysis of the tube arrangements. The automation process includes the geometry generation, meshing and then post processing of the results with the use of a Python code. The results show that the model can predict performance metrics, offering valuable insights for the effects of the design parameters and configuration of radial flow heat exchangers.

Keywords: CFD, Heat Exchangers, Automation, Performance, Heat Transfer, Tube banks, Zones.

Acknowledgements

We would like to thank our supervisors Michal Nitulescu and August Skoglund at GKN Aerospace for their guidance and reviews throughout the thesis. We would also like to express our gratitude to Jonas Bredberg for sharing his valuable insights from his previous experience with radial flow heat exchangers. We would also like to extend our gratitude to Isak Lundgren for his assistance in helping running our simulations on the cluster easily.

Chalmers University of Technology has been incredibly supportive. We extend our thanks to Carlos Xisto from the Division of Fluid Dynamics at the Department of Mechanics and Maritime Sciences for taking the time to serve as the examiner for this thesis.

Finally, we appreciate the support, help, and enjoyable fika times with our colleagues at GKN.

Jay Baviskar, Gothenburg, June 2024
Yasser Alrifai, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

API	Application Programming Interface
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
ESDU	Engineering Sciences Data Unit
HEDH	Heat Exchanger Design Handbook
HTC	Heat Transfer Coefficient
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
PW	Pratt and Whitney
VDI	Verein Deutscher Ingenieure

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Indices

l	Longitudinal
t	Transverse
T	Tube
w	Wall
max	Maximum
lam	Laminar
$turb$	Turbulent

Variables

h	Heat transfer coefficient
Q	Heat flux
ΔT	Temperature difference
A	Total area
P_r	Prandtl number
ν	Kinematic viscosity
α	Thermal diffusivity
μ	Dynamic viscosity
C_p	Specific heat
k	Thermal conductivity
Re	Reynolds number
v	Velocity

L	Characteristic length
N_u	Nusselt number
D	Diameter of tube
T	Temperature
Sl	Longitudinal pitch
St	Transverse pitch
Pl	Longitudinal pitch ratio
St	Transverse pitch ratio
k	Turbulent kinetic energy
ϵ	Turbulent dissipation rate
w	Specific dissipation rate
SST	Shear Stress Transport
HT	Total Heat transfer
dP	Total pressure drop

Contents

List of Acronyms	viii
Nomenclature	x
List of Figures	xvi
List of Tables	xviii
1 Introduction	1
1.1 Background	1
1.1.1 Interdisciplinary Design Considerations	1
1.1.2 Objective and Performance Measures	1
1.1.3 Automation and Optimization in Design	1
1.2 Radial Flow Heat Exchangers' Applications in Aviation	2
1.3 Literature Review	2
1.3.1 Understanding Heat Transfer and Fluid Dynamics Basics in Heat Exchangers	3
1.3.2 Learning from Crossflow Heat Exchangers	3
1.3.3 Adapting Known Correlations and Methods	3
1.3.4 Conclusion	3
1.4 Limitations	3
2 Theory	5
2.1 Types of Heat Exchangers	5
2.2 Performance Parameters	5
2.2.1 Heat Transfer Coefficient (HTC)	5
2.2.2 Prandtl Number	6
2.2.3 Reynolds Number	6
2.2.4 Nusselt Number	7
2.2.5 Number of tubes/Weight	7
2.3 External flow around Tube Banks	7
2.3.1 Tube Arrangements and Pitch	7
2.3.2 Impact on Performance	9
2.3.3 Concept of narrowest region	11
2.4 Computational Fluid Dynamics (CFD)	12
2.4.1 Continuity Equation	13
2.4.2 Momentum Equation	13

2.4.3	Energy Equation	13
2.4.4	K-omega Turbulence Model	13
2.4.5	K-epsilon Turbulence Model	14
2.4.6	Wall Treatment and y^+ Values	14
3	Methodology	15
3.1	Geometry generation	15
3.2	Mesh generation	17
3.3	Simulation Setup	18
3.3.1	Boundary Conditions	18
3.3.2	Solver Settings	19
3.3.2.1	Model	19
3.3.2.2	Turbulence Model	19
3.3.2.3	Discretisation Schemes and Convergence criteria	19
3.4	Post-processing	20
3.5	Test Matrix	21
3.6	Correlation Validation	24
3.7	Mesh Independence Study	24
4	Results and Discussion	26
4.1	Mesh Independence Study Results	26
4.2	Correlation Validation	27
4.3	Results for an example case	30
4.4	Effect of varying St/D	33
4.5	Effect of varying Sl/D	36
4.6	Constant zoning vs. Variable zoning	38
4.7	Effect of zones	46
4.8	Overall Domain Performance:	51
4.8.1	Constant St/D with 4 zones	51
4.8.2	Constant St/D with 3 zones	53
4.8.3	Variable St/D with 4 zones	53
4.8.4	Variable St/D with 3 zones	53
4.8.5	Performance discrepancies between CFD and Correlations	57
4.8.5.1	4 Zones	57
4.8.5.2	3 Zones	59
4.9	Misaligned flow	61
4.10	Use of SpaceClaim	61
4.11	Future Work	61
5	Conclusion	63
	Bibliography	64
A	Appendix 1	I
A.1	Results for Sl125 St13 13 13 13 case	I
A.2	Results for Sl125 St13 13 13 case	II
A.3	Results for Sl125 St14 14 14 14 case	II

A.4	Results for Sl125 St14 14 14 case	III
A.5	Results for Sl125 St16 16 16 16 case	III
A.6	Results for Sl125 St16 16 16 16 case	IV
A.7	Results for Sl125 St16 16 16 case	IV
A.8	Results for Sl125 St16 16 case	V
A.9	Results for Sl125 St16 case	VI
A.10	Results for Sl125 St18 18 18 18 case	VII
A.11	Results for Sl125 St18 18 18 case	VII
A.12	Results for Sl125 St23 18 13 case	VIII
A.13	Results for Sl125 St25 18 16 13 case	VIII
A.14	Results for Sl125 St27 2 13 case	IX
A.15	Results for Sl125 St2 15 13 case	X
A.16	Results for Sl125 St2 17 14 13 case	X
A.17	Results for Sl125 St2 2 2 2 case	XI
A.18	Results for Sl125 St2 2 2 case	XI
A.19	Results for Sl125 St3 2 17 13 case	XII
A.20	Results for Sl15 St13 13 13 13 case	XII
A.21	Results for Sl15 St13 13 13 case	XIII
A.22	Results for Sl15 St14 14 14 14 case	XIII
A.23	Results for Sl15 St14 14 14 case	XIV
A.24	Results for Sl15 St16 16 16 case	XV
A.25	Results for Sl15 St18 18 18 18 case	XV
A.26	Results for Sl15 St18 18 18 case	XVI
A.27	Results for Sl15 St23 18 13 case	XVII
A.28	Results for Sl15 St25 18 16 13 case	XVII
A.29	Results for Sl15 St27 2 13 case	XVIII
A.30	Results for Sl15 St2 15 13 case	XIX
A.31	Results for Sl15 St2 17 14 13 case	XIX
A.32	Results for Sl15 St2 18 16 14 case	XX
A.33	Results for Sl15 St2 2 2 2 case	XX
A.34	Results for Sl15 St2 2 2 case	XXI
A.35	Results for Sl15 St3 2 17 13 case	XXI
A.36	Results for Sl175 St13 13 13 13 case	XXII
A.37	Results for Sl175 St13 13 13 case	XXII
A.38	Results for Sl175 St14 14 14 14 case	XXIII
A.39	Results for Sl175 St14 14 14 case	XXIII
A.40	Results for Sl175 St16 16 16 16 case	XXIV
A.41	Results for Sl175 St16 16 16 case	XXIV
A.42	Results for Sl175 St18 18 18 18 case	XXV
A.43	Results for Sl175 St18 18 18 case	XXV
A.44	Results for Sl175 St23 18 13 case	XXVI
A.45	Results for Sl175 St25 18 16 13 case	XXVI
A.46	Results for Sl175 St27 2 13 case	XXVII
A.47	Results for Sl175 St2 15 13 case	XXVIII
A.48	Results for Sl175 St2 17 14 13 case	XXVIII
A.49	Results for Sl175 St2 18 16 14 case	XXIX

A.50 Results for Sl175 St2 2 2 2 case	XXIX
A.51 Results for Sl175 St2 2 2 case	XXX
A.52 Results for Sl175 St3 2 17 13 case	XXX
A.53 Results for Sl2 St13 13 13 13 case	XXXI
A.54 Results for Sl2 St13 13 13 case	XXXI
A.55 Results for Sl2 St14 14 14 14 case	XXXII
A.56 Results for Sl2 St14 14 14 case	XXXII
A.57 Results for Sl2 St16 16 16 16 case	XXXIII
A.58 Results for Sl2 St16 16 16 case	XXXIII
A.59 Results for Sl2 St18 18 18 18 case	XXXIV
A.60 Results for Sl2 St18 18 18 case	XXXIV
A.61 Results for Sl2 St23 18 13 case	XXXV
A.62 Results for Sl2 St25 18 16 13 case	XXXV
A.63 Results for Sl2 St27 2 13 case	XXXVI
A.64 Results for Sl2 St2 15 13 case	XXXVII
A.65 Results for Sl2 St2 17 14 13 case	XXXVII
A.66 Results for Sl2 St2 2 2 2 case	XXXVIII
A.67 Results for Sl2 St2 2 2 case	XXXVIII
A.68 Results for Sl2 St3 2 17 13 case	XXXIX

List of Figures

2.1	Tube Arrangements illustrating Sl/D =Longitudinal pitch and St/D =Transverse pitch	8
2.2	Example of Radial Arrangements in a Tube Bundle	8
2.3	Figures 2.3(a) and 2.3(b) illustrating the narrowest region as the horizontal gap between tubes, irrespective of Sl values	11
2.4	Illustrating the transition in the narrowest region in staggered tube arrangements below a certain Sl ratio	12
3.1	Staggered geometry	15
3.2	Implementation of zones in the geometry	16
3.3	Bulk temperature sections	21
3.4	Bulk velocity sections	21
3.5	A case depicting the calculation of average St/D ratio for a zone.	23
3.6	A rectangular domain constant $Sl/D = 1.5$ and $St/D = 1.25$	24
3.7	Geometry of Mesh independence studies	25
4.1	Mesh independence study results	27
4.2	Correlation Validation with Constant $St/D=1.5$	28
4.3	Correlation Validation with Constant $Sl/D=1.5$	29
4.4	Contours obtained from Fluent for all the simulations	31
4.5	Plots for example case with $Sl/D=1.5$ and $St/D=[1.6,1.6,1.6,1.6]$	32
4.6	Varying St/D for constant $Sl/D = 1.25$	34
4.7	Varying St/D for constant $Sl/D = 2$	35
4.8	Constant zonewise Sl/D vs varying St/D	36
4.9	Constant St/D vs Varying Sl/D for scarcely packed case	37
4.10	Constant St/D vs Varying Sl/D for densely packed case	37
4.11	Constant zonewise St/D vs varying Sl/D	38
4.12	Constant vs Variable zoning for a scarcely packed case	41
4.13	Constant vs Variable zoning for a densely packed case	42
4.14	Comparing HT/dP performance for all constant and variable zoning cases for 4 zones	43
4.15	Comparing HT/dP per tube for all constant and variable zoning cases for 4 zones	44
4.16	Scarcely packed case trimmed only upto 3 zones	45
4.17	4 zones vs 3 zones for a scarcely packed case $Sl/D = 2$ and $St/D=2$	47
4.18	4 zones vs 3 zones for a densely packed case $Sl/D = 1.25$ and $St/D=1.3$	48

4.19	Performance plots varying from 1 to 5 zones for case Sl125_St16_16_16_16	49
4.20	Effect of varying number of zones from 1 to 5 for a single case Sl15_St16_16_16_16	50
4.21	Performance of all cases - 4 zones vs 3 zones	51
4.22	Heatmaps showing the performance of a domain of 4 zones with constant St/D for different parameters	52
4.23	Heatmaps showing the performance of a domain of 3 zones with constant St/D for different parameters	54
4.24	Heatmaps showing the performance of a domain of 4 zones with variable St/D for different parameters	55
4.25	Heatmaps showing the performance of a domain of 3 zones with variable St/D for different parameters	56
4.26	Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant Sl/D with 4 zones	57
4.27	Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant St/D with 4 zones	58
4.28	Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant Sl/D with 4 zones	59
4.29	Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant St/D with 3 zones	60

List of Tables

3.1	Geometry parameters	16
3.2	Boundary conditions and Simulation setup in ANSYS FLUENT . . .	20
3.3	Test Matrix	22
3.5	Mesh Parameters for every case	25
4.1	Total heat transfer and pressure drop values for all the cases	26
4.2	Zukasukas Nu and dP Deviation for varying Sl/D and constant St/D=1.5	28
4.3	Zukasukas Nu and dP Deviation for varying St/D and constant Sl/D=1.5	29
4.4	Comparing Performance Parameters of Varying vs Constant St/D per Zone for 3 Zones	39
4.5	Comparing Performance Parameters of Varying vs Constant St/D per Zone for 4 Zones	40
4.6	Difference in performance for a scarcely packed case with 4 zones and trimmed off 4th zone	45
A.1	Results for Sl125 St13 13 13 13 case	I
A.2	Results for Sl125 St13 13 13 case	II
A.3	Results for Sl125 St14 14 14 14 case	II
A.4	Results for Sl125 St14 14 14 case	III
A.5	Results for Sl125 St16 16 16 16 16 case	III
A.6	Results for Sl125 St16 16 16 16 case	IV
A.7	Results for Sl125 St16 16 16 case	IV
A.8	Results for Sl125 St16 16 case	V
A.9	Results for Sl125 St16 case	VI
A.10	Results for Sl125 St18 18 18 18 case	VII
A.11	Results for Sl125 St18 18 18 case	VII
A.12	Results for Sl125 St23 18 13 case	VIII
A.13	Results for Sl125 St25 18 16 13 case	VIII
A.14	Results for Sl125 St27 2 13 case	IX
A.15	Results for Sl125 St2 15 13 case	X
A.16	Results for Sl125 St2 17 14 13 case	X
A.17	Results for Sl125 St2 2 2 2 case	XI
A.18	Results for Sl125 St2 2 2 case	XI
A.19	Results for Sl125 St3 2 17 13 case	XII
A.20	Results for Sl15 St13 13 13 13 case	XII
A.21	Results for Sl15 St13 13 13 case	XIII
A.22	Results for Sl15 St14 14 14 14 case	XIII

A.23 Results for Sl15 St14 14 14 case	XIV
A.24 Results for Sl15 St16 16 16 case	XV
A.25 Results for Sl15 St18 18 18 18 case	XV
A.26 Results for Sl15 St18 18 18 case	XVI
A.27 Results for Sl15 St23 18 13 case	XVII
A.28 Results for Sl15 St25 18 16 13 case	XVII
A.29 Results for Sl15 St27 2 13 case	XVIII
A.30 Results for Sl15 St2 15 13 case	XIX
A.31 Results for Sl15 St2 17 14 13 case	XIX
A.32 Results for Sl15 St2 18 16 14 case	XX
A.33 Results for Sl15 St2 2 2 2 case	XX
A.34 Results for Sl15 St2 2 2 case	XXI
A.35 Results for Sl15 St3 2 17 13 case	XXI
A.36 Results for Sl175 St13 13 13 13 case	XXII
A.37 Results for Sl175 St13 13 13 case	XXII
A.38 Results for Sl175 St14 14 14 14 case	XXIII
A.39 Results for Sl175 St14 14 14 case	XXIII
A.40 Results for Sl175 St16 16 16 16 case	XXIV
A.41 Results for Sl175 St16 16 16 case	XXIV
A.42 Results for Sl175 St18 18 18 18 case	XXV
A.43 Results for Sl175 St18 18 18 case	XXV
A.44 Results for Sl175 St23 18 13 case	XXVI
A.45 Results for Sl175 St25 18 16 13 case	XXVI
A.46 Results for Sl175 St27 2 13 case	XXVII
A.47 Results for Sl175 St2 15 13 case	XXVIII
A.48 Results for Sl175 St2 17 14 13 case	XXVIII
A.49 Results for Sl175 St2 18 16 14 case	XXIX
A.50 Results for Sl175 St2 2 2 2 case	XXIX
A.51 Results for Sl175 St2 2 2 case	XXX
A.52 Results for Sl175 St3 2 17 13 case	XXX
A.53 Results for Sl2 St13 13 13 13 case	XXXI
A.54 Results for Sl2 St13 13 13 case	XXXI
A.55 Results for Sl2 St14 14 14 14 case	XXXII
A.56 Results for Sl2 St14 14 14 case	XXXII
A.57 Results for Sl2 St16 16 16 16 case	XXXIII
A.58 Results for Sl2 St16 16 16 case	XXXIII
A.59 Results for Sl2 St18 18 18 18 case	XXXIV
A.60 Results for Sl2 St18 18 18 case	XXXIV
A.61 Results for Sl2 St23 18 13 case	XXXV
A.62 Results for Sl2 St25 18 16 13 case	XXXV
A.63 Results for Sl2 St27 2 13 case	XXXVI
A.64 Results for Sl2 St2 15 13 case	XXXVII
A.65 Results for Sl2 St2 17 14 13 case	XXXVII
A.66 Results for Sl2 St2 2 2 2 case	XXXVIII
A.67 Results for Sl2 St2 2 2 case	XXXVIII
A.68 Results for Sl2 St3 2 17 13 case	XXXIX

1

Introduction

1.1 Background

This chapter introduces the context and motivation for the study of radial flow heat exchangers, outlining the interdisciplinary nature of heat exchanger design and the importance of automation and optimization in the process. This chapter also provides a brief overview of the literature review conducted to inform this thesis.

1.1.1 Interdisciplinary Design Considerations

The design of heat exchangers involves a complex interplay of physical principles and necessitates a comprehensive understanding across several engineering disciplines. This process is inherently iterative, leveraging computational tools to predict the efficiency of a heat exchanger. Critical knowledge from fluid mechanics, heat transfer, thermodynamics, and materials science plays a pivotal role in this multidisciplinary endeavor. The interplay of the different engineering disciplines (e.g. Solid Mechanics, Fluid Mechanics/Thermodynamics) is what ultimately decides the outcome for the design.

1.1.2 Objective and Performance Measures

This thesis aims to evaluate how different design parameters of a heat exchanger influence its performance. Key performance measures include the heat transfer rate, pressure drop, and cost implications. Although the focus is not on the overall cost, the study aims to identify the best performing design within the requirements that are later introduced in this thesis, by considering factors such as spacing and layout, with a fixed tube diameter. The ultimate goal is to enhance heat transfer efficiency while minimizing pressure losses.

1.1.3 Automation and Optimization in Design

At the core of identifying the most suitable design is employing a parametric study through the automation of a Computational Fluid Dynamics(CFD) workflow. This endeavor seeks to strike a balance by enhancing the heat transfer rate without incurring significant pressure drops. The ambition is to develop an automated system that generates geometry and mesh from specific inputs, thereby streamlining the CFD simulations. With the advent of CFD automation, the transition from geometry generation to solving and analyzing results becomes seamless. This technology is

pivotal for the precise optimization of design parameters, essential for understanding the effects of design modifications on a heat exchanger's performance. By enabling rapid prototyping and testing, automated workflows pave the way for more effective and efficient heat exchanger designs.

1.2 Radial Flow Heat Exchangers' Applications in Aviation

Radial (Annular) Flow heat exchangers can be an area of interest in aviation, where efficiency, reliability, and optimization of space and weight are critical. These devices, which facilitate heat transfer between two or more fluids of different temperatures without mixing them, could be used for managing the thermal loads within an aircraft's systems.

In aviation, radial flow heat exchangers could be utilized for their compact design and heat transfer efficiency, making them ideal for applications such as engine oil cooling, fuel system thermal management, and air conditioning systems. The unique design of radial heat exchangers allows for effective heat dissipation in the confined spaces of an aircraft, contributing to overall weight reduction and fuel efficiency, crucial aspects in aerospace engineering [14]. Furthermore, their ability to maintain operational integrity under varying conditions of pressure and temperature aligns with the stringent safety and performance requirements of the aviation industry. As such, the design and optimization of radial flow heat exchangers are subjects of significant interest, driving advancements in materials science and thermal engineering to enhance the efficiency and reliability of aircraft systems [23].

Among the various companies and shell and tube heat exchangers explored, Hugo Petersen GmbH was the sole company identified that had researched, developed, and implemented radial flow heat exchangers, primarily for use in chemical plants. However, GKN Aerospace has also explored similar heat exchangers recently, filing a patent for their design under the name Exhaust Cone Heat Exchangers [7]. In aviation, there is a growing need for sustainable solutions, particularly with alternative fuels like liquid hydrogen. These fuels require preheating before combustion, making the utilization of exhaust gases for preheating efficient, especially when integrated into the engine nacelle shape. This demonstrates the significant potential for these heat exchangers in the aerospace industry.

1.3 Literature Review

This section examines the current state of knowledge on radial flow heat exchangers, an area with limited direct research. The exploration relies on foundational theories and studies from related fields to derive insights and methodologies potentially applicable to radial flow heat exchangers.

1.3.1 Understanding Heat Transfer and Fluid Dynamics Basics in Heat Exchangers

Essential heat transfer principles are covered in texts such as *Principles of Heat Transfer* by Kreith & Manglik (2018) [14] and *Fundamentals of Heat Exchanger Design* by Shah & Sekulic (2003) [23]. Other sources regarding heat transfer within heat exchangers include, but are not limited to, Bird, Stewart, & Lightfoot (2002) [4] and Incropera, DeWitt, Bergman, & Lavine (2007) [11]. These resources provide a fundamental understanding necessary for grasping the complexities of heat exchanger operations, laying the groundwork for the exploration of radial flow heat exchangers.

1.3.2 Learning from Crossflow Heat Exchangers

Given the scarcity of literature on radial flow heat exchangers, insights from crossflow heat exchanger studies will be put into use in this thesis. Research by Zukauskas (1972) [27] and guidelines from ESDU (1973) and HEDH (1987) [9] offer perspectives on fluid and heat interactions within these systems. Though focused on crossflow mechanisms, these findings suggest underlying principles that may also apply to radial flow configurations, offering a basis for hypothesis and analogy.

1.3.3 Adapting Known Correlations and Methods

The adaptation of existing correlations and methodologies to radial flow heat exchangers is examined. The work of Grimison (1937), providing equations for fluid dynamics and heat transfer in crossflows, serves as a potential model for understanding similar processes in radial flows. Additionally, resources such as the *VDI Heat Atlas* (2010) [25] and the *Heat Exchanger Design Handbook* (Schlunder & International Center for Heat and Mass Transfer, 1987) [9] present tools and data which, though not specifically tailored for radial flow, can inform design and evaluation strategies.

1.3.4 Conclusion

Through the combination of knowledge from heat transfer basics, crossflow studies, and fundamental principles of fluid dynamics, a foundation is laid for future research into radial flow heat exchangers. This review demonstrates the potential for applying established scientific concepts in new contexts, identifies knowledge gaps, and proposes directions for future inquiry. It highlights the necessity of cross-disciplinary application of known theories to deepen the understanding of radial flow heat exchangers.

1.4 Limitations

Due to the complexity of the subject matter, this thesis is not without limitations. When it comes to the design of the heat exchanger, the degrees of freedom are

plenty, and the study will focus on a limited set of parameters. The study will not delve into the material selection process, which is a critical aspect of heat exchanger design. Additionally, the study will not consider the impact of fouling on the heat exchanger's performance, which is a significant concern in real-world applications. The study will also not consider transient effects, focusing solely on steady-state conditions. The things kept constant in the study are the following:

1. 2D Geometry
2. Tube Diameter
3. Radial Section Region
4. Inlet and Outlet Conditions
5. Layout of Pipes: Staggered
6. Constant Wall (tube) Temperature
7. Inlet conditions of fluid entering

2

Theory

This chapter will provide an overview of the theoretical concepts and principles relevant to the study of heat exchangers, fluid dynamics, and computational fluid dynamics (CFD). Understanding these fundamental concepts is essential for analyzing the performance of heat exchangers, improving upon their design, and interpreting the results obtained from numerical simulations.

2.1 Types of Heat Exchangers

There are various types of heat exchangers, each tailored for specific applications and operating conditions [9]. Some examples include:

- **Shell and Tube Heat Exchangers:** These consist of a series of tubes that separate the fluids. The design is robust and can handle high pressures, making it a popular choice in many industries [23]. The thesis will focus on this type of heat exchanger.
- **Plate Heat Exchangers:** Comprising multiple, thin, slightly-separated plates, these exchangers are known for their efficiency in heating, cooling, and heat recovery processes where space and weight are significant concerns [25].
- **Double Pipe Heat Exchangers:** These are the simplest type of heat exchanger, consisting of one pipe inside another. They are used in small industries due to their low cost and simplicity, although they are less efficient compared to other types [22].
- **Finned Tube Heat Exchangers:** Designed to maximize the heat transfer area by adding fins to the tubes, these are often used in applications involving air, such as in car radiators and air conditioners [9].

2.2 Performance Parameters

Below are the performance parameters discussed and used during the thesis as measures for performance comparison:

2.2.1 Heat Transfer Coefficient (HTC)

The Heat Transfer Coefficient (HTC) is a pivotal parameter in the realm of thermodynamics and heat transfer, serving as a quantifier of the heat exchange efficiency between a solid surface and a fluid in contact with it. Defined as the amount of

heat transferred per unit time, per unit area, and per unit temperature difference, it encapsulates the influence of material properties, flow characteristics, and surface conditions [14]. Mathematically, it is expressed as:

$$h = \frac{Q}{A\Delta T} = \frac{Q}{A(T_{wall} - T_{bulk})} \quad (2.1)$$

where h represents the heat transfer coefficient in watts per square meter-kelvin ($\text{W}/\text{m}^2\text{K}$), (Q) is the total heat transfer rate in watts (W), (A) denotes the area through which heat transfer occurs in square meters (m^2), and ΔT is the temperature difference between the fluid and the surface in kelvin (K). The HTC is affected by numerous factors, including the type of fluid, its velocity, the surface material, and the presence of any fouling on the heat transfer surfaces [4]. High values of HTC indicate efficient heat transfer, which is desirable in heat exchangers. A higher value of the HTC can help enhance energy efficiency and performance [11].

2.2.2 Prandtl Number

The Prandtl number (Pr) is a dimensionless number that relates the momentum diffusivity (kinematic viscosity) to the thermal diffusivity of a fluid. It is used in heat transfer calculations, particularly in predicting the boundary layer flow characteristics over a flat plate and in tube flows [23]. The Prandtl number is defined as:

$$Pr = \frac{\nu}{\alpha} \quad (2.2)$$

where ν is the kinematic viscosity of the fluid (the ratio of the fluid's dynamic viscosity μ to its density ρ), and α is the thermal diffusivity (the ratio of the thermal conductivity k to the product of density ρ and specific heat capacity at constant pressure C_p). The equation can also be represented as:

$$Pr = \frac{\mu C_p}{k} \quad (2.3)$$

The Prandtl number serves as an indicator of the relative thickness of the momentum and thermal boundary layers; a high Prandtl number suggests that the momentum diffusivity is dominant, leading to a thicker velocity boundary layer compared to the thermal boundary layer [4]. This number is crucial in the design and analysis of heat exchangers and other thermal systems, as it helps in understanding the fluid's thermal and flow behavior [14].

2.2.3 Reynolds Number

The Reynolds number (Re) is essential for understanding external fluid flow around objects, defined as:

$$Re = \frac{\rho v L}{\mu} \quad (2.4)$$

where (ρ) is the fluid density (kg/m^3), (v) the fluid velocity (m/s), (L) the characteristic length (m), and (μ) the dynamic viscosity ($\text{Pa} \cdot \text{s}$) [4]. This dimensionless

number helps determine whether the flow is laminar or turbulent around objects like cylinders or in heat exchangers, which is crucial for designing efficient systems [11].

Laminar flow, smooth and orderly, occurs at low Reynolds numbers, while turbulent flow, characterized by chaotic motions, appears at higher values. The transition between these states depends on the object's shape and the flow conditions [25]. Understanding and predicting these flow regimes is vital for optimizing heat transfer and minimizing drag in engineering applications [23].

2.2.4 Nusselt Number

The Nusselt number (Nu) is a dimensionless number that signifies the enhancement of heat transfer through convection relative to that of pure conduction. It is a critical parameter in the study of heat transfer in fluids and is defined as:

$$Nu = \frac{hL}{k} \quad (2.5)$$

where h is the heat transfer coefficient, L is the characteristic length, typically the hydraulic diameter in meters (m), and k is the thermal conductivity of the fluid in watts per meter-kelvin (W/mK) [25]. The Nusselt number provides a measure of the convective heat transfer occurring at a surface relative to the conductive heat transfer within the fluid [14]. A higher Nusselt number indicates more effective convective heat transfer, which is advantageous in applications such as heat exchangers, where maximizing heat transfer efficiency is desired [23].

2.2.5 Number of tubes/Weight

As previously mentioned in section 1.2, given its considerable potentiality in aircraft applications, it is important that we also reflect upon the weight of the heat exchanger. For simplicity, we define it solely based on the number of tubes. More tubes correspond to increased weight. Another reason behind selecting this as a performance parameter is to identify instances where similar performance outcomes are achieved while utilizing fewer tubes.

2.3 External flow around Tube Banks

2.3.1 Tube Arrangements and Pitch

The configuration of tubes within shell and tube heat exchangers significantly influences their operational efficiency, can be categorized into two types of patterns, square (inline) and triangular (staggered) patterns. These arrangements, coupled with the strategic selection of longitudinal and transverse pitches, play pivotal roles in optimizing external flow dynamics, thermal performance, and pressure drop.

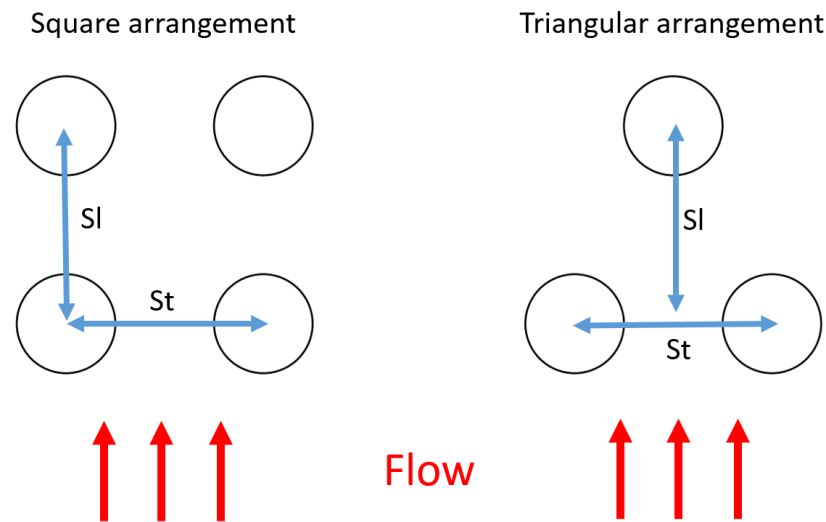


Figure 2.1: Tube Arrangements illustrating Sl/D =Longitudinal pitch and St/D =Transverse pitch

Square/Inline Arrangement: This layout positions tubes at the corners of squares, facilitating maintenance due to easier access to tube surfaces. It is particularly advantageous when the shell-side fluid is clean, minimizing the risk of fouling [14].

Triangular/Staggered Arrangement: In this configuration, tubes are arranged at the corners of equilateral triangles. This compact arrangement enhances heat transfer efficiency by maximizing the surface area available for heat exchange, suitable for scenarios requiring intensive thermal performance [23].

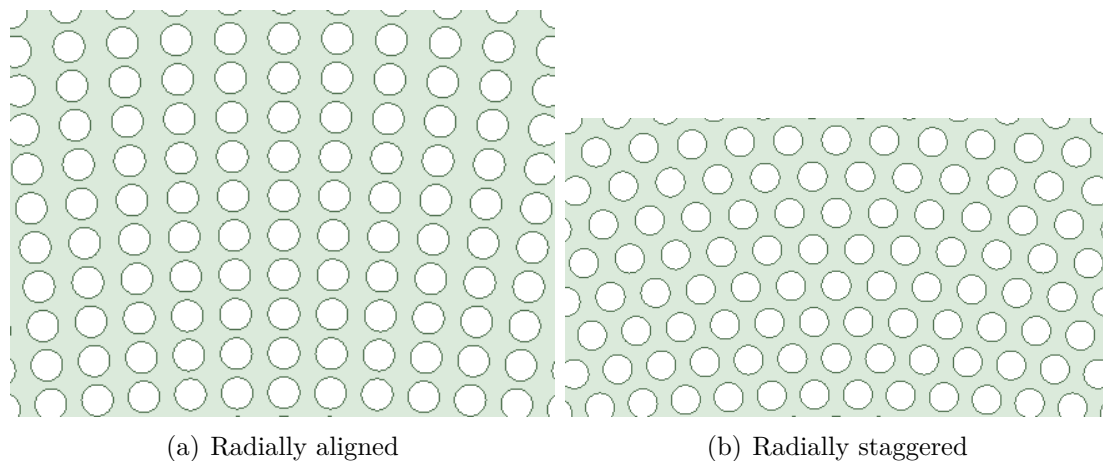


Figure 2.2: Example of Radial Arrangements in a Tube Bundle

Longitudinal Pitch (Sl) and **Transverse Pitch (St)** determine the center-to-center distance between tubes in parallel and perpendicular directions to the flow, respectively. They affect the tube bundle's density and efficiency.

$$P_l = \frac{S_l}{D_T}, \quad P_t = \frac{S_t}{D_T} \quad (2.6)$$

where P_l and P_t are non-dimensionalised numbers representing the longitudinal and transverse pitch ratios. and D_T is the tube's outer diameter.

2.3.2 Impact on Performance

The interplay between tube arrangement and pitch decisively impacts the heat exchanger's thermal performance and pressure drop characteristics. These are mainly dominated by the boundary layer formations, flow separations and the flow effective areas. For example, in the case of inline arrangements, if the tubes are placed too close to each other, the rows behind get shielded by the rows ahead of them. This reduces the effective area through which the fluid medium and tubes are going to exchange heat. One can place them far away from each other which reduces the effective area again since now one can fit less number of pipes in the same volume. Staggered arrangement on the other hand, a greater portion of the tube area stays in contact with the fluid which enhances heat transfer. The main focus of the project will be on staggered grid arrangements.

Thermal Performance: Nusselt number is the most common choice of a parameter to compare when it comes to thermal efficiency. One of the more commonly used correlations for obtaining the average HTC or Nusselt number is the Zukauskas correlation eq. (2.7) with Zukauskas being the more recent one. A very comprehensive work was carried out by Zukauskas [27] on flows through tube bundles. The study correlated the performance parameters over very large ranges of Pr, Re, Sl/D, St/D (non-dimensionalised pitch). It's important to note that all the other correlations mentioned subsequently, were developed for scenarios with a constant transverse pitch (St) and a constant longitudinal pitch (Sl).

$$\overline{Nu} = C_n Re_{D,max}^m Pr^{0.36} \left(\frac{Pr}{Pr_w} \right)^{0.25} \quad (2.7)$$

where, C_n is a correction factor, Pr and Pr_w are Prandtl and wall Prandtl numbers respectively, and Re_{max} is the maximum Reynolds number occurring in the tube bank based on the concept of narrowest section discussed in a later section (section 2.3.3). The Zukauskas correlations are valid only for $1000 < Re < 20000$ and for number of tube rows greater than 19.

In instances where the number of rows is fewer than the specified threshold, a correction factor has to be applied to the correlations to get the appropriate average HTCs for the rows in the beginning. This is because the first few rows behave as a turbulence generating grids. The HTC for the first row in the bank is approximately that of a single row of tubes. The rows behind introduce turbulence in the flow which increases the HTC of the tubes. The convection coefficient remain almost steady after the first few rows and hence the above relations hold quite accurate for tube bundles comprising more than 10 rows. Both the relations for less than 10 rows along with their correction factors - C_n , C_1 and m , could be found in section 7.6 in Fundamentals of Heat Transfer by F. Incropera and others[11].

A more generalised form of Zukauskas relation could be found in his own works [27].

$$\overline{Nu_D} = 0.35C_n Re_D^{0.6} Pr^{0.36} \left(\frac{Pr}{Pr_w}\right)^{0.25} \left(\frac{S_t}{S_l}\right)^{0.2} \quad (2.8)$$

The CFD results are also going to be compared with 2 more correlations developed by an English research organisation - Engineering Sciences Data Unit(ESDU), equation (2.9), and the one recommended by the Heat Exchanger Design Handbook(HEDH) comprising a set of equations - (2.10), (2.11), (2.12) and (2.13).

$$Nu = aRe^m Pr^{0.34} F_1 F_2 \quad (2.9)$$

where, a and m are constants, F_2 is a tube correction factor, and F_1 is a property correction factor which accounts the change for Prandtl number at walls.

The HEDH correlations are given as,

$$Nu = Nu_m f_N \quad (2.10)$$

$$Nu_m = 0.3 + \sqrt{Nu_{m,lam}^2 + Nu_{m,turb}^2} \quad (2.11)$$

$$Nu_{m,lam} = 0.664 Re^{0.5} Pr^{1/3} \quad (2.12)$$

$$Nu_{m,turb} = \frac{0.037 Re^{0.8} Pr}{1 + 2.443 Re^{-0.1} (Pr^{2/3} - 1)} \quad (2.13)$$

Pressure Drop: While staggered configurations offer superior thermal performance, they can also result in higher pressure drops because of the more restricted flow path. Conversely, square arrangements, by providing a less obstructed flow, can reduce pressure drop at the expense of thermal efficiency. A correlation was developed and presented by Zukasukas[27] based on maximum fluid velocity V_{max} in the tube bank.

$$\Delta P = N_L \chi \left(\frac{\rho V^2}{2}\right) f \quad (2.14)$$

Where,

N_L is number of rows,

χ is a correction factor that is applied for different St/Sl ratios and,

f is a friction factor that varies with varying Reynolds number.

Both correlations - thermal and pressure drop are dependent on V_{max} occurring in the tube banks. Hence, increasing the number of tubes per row for the same volume increases the heat transfer but also increases the pressure drop. Therefore, a careful selection and optimization of tube arrangements and pitches are thus critical for designing efficient heat exchangers, necessitating a balanced approach to maximize heat transfer capabilities and minimize fluid resistance and maintenance requirements.

2.3.3 Concept of narrowest region

All the thermal correlations discussed in the previous section are based on the maximum Reynolds number and maximum velocity occurring in the tube banks. Hence, if the density and molecular viscosity is to be assumed constant throughout the tube bank, the maximum Reynolds number corresponds to maximum velocity in the section. For an incompressible flow, according to conservation of mass, velocity will be higher if it has to pass through narrower regions and vice versa. Mathematically, the equation simply becomes

$$A_1 V_1 = A_2 V_2 \quad (2.15)$$

Hence to find maximum velocity in a tube bank, the narrowest region in the arrangement has to be investigated. In the case of inline tube arrangements, it is intuitive that it would be the summation of gaps between the tubes OR the area blocked by the tubes subtracted from the total inlet area. Hence, the maximum velocity can simply be expressed in terms of tube diameter and St as [11],

$$V_{max} = \frac{St}{St - D} V_1 \quad (2.16)$$

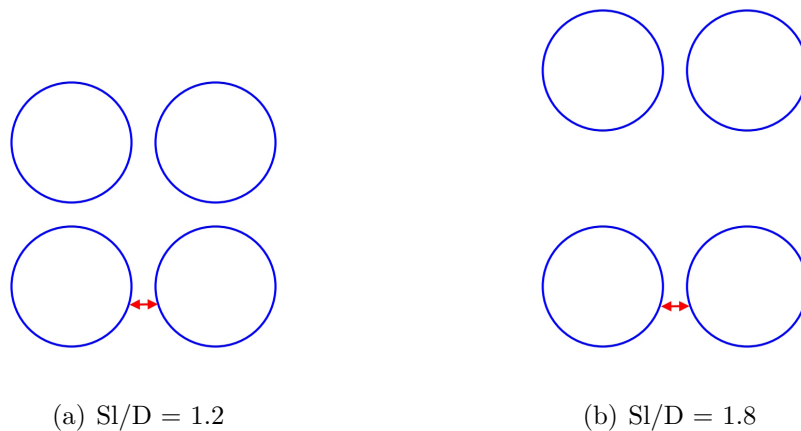


Figure 2.3: Figures 2.3(a) and 2.3(b) illustrating the narrowest region as the horizontal gap between tubes, irrespective of Sl values

In case of inline arrangement, figures 2.3 illustrate that the narrowest region will always be horizontal gap between the tubes no matter what the Sl values are, but this does not hold true in the case of staggered tube arrangements.

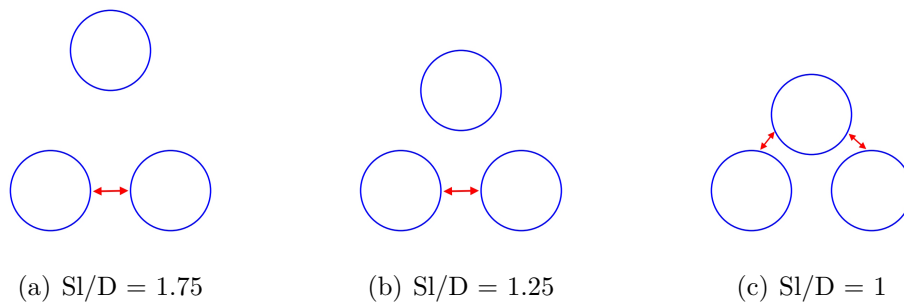


Figure 2.4: Illustrating the transition in the narrowest region in staggered tube arrangements below a certain Sl ratio

In case of staggered tube banks, the narrowest region changes its position below a certain threshold of **critical Sl** . Fig 2.4 portrays if one keeps on reducing the longitudinal pitch, the narrowest region no longer remains the area between the tubes in the horizontal direction, but the area between the diagonal tube. Hence, if the diagonal pitch becomes less than half of transverse pitch, then the narrowest region will switch. Mathematically,

$$2(S_D - D) < (S_t - D) \quad (2.17)$$

then,

$$V_{max} = \frac{S_t}{2(S_D - D)} V_1 \quad (2.18)$$

where,

$$S_D = \left[Sl^2 + \left(\frac{St}{2} \right)^2 \right]^{\frac{1}{2}} \quad (2.19)$$

If the diagonal pitch greater than half of transverse pitch, then the narrowest region will still remain as horizontal distance between tubes and will be calculated using the relation 2.16.

2.4 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is a powerful tool used to simulate fluid flow and heat transfer phenomena in engineering applications. By solving the governing equations of fluid dynamics numerically, CFD enables engineers to analyze complex flow behaviors, optimize designs, and predict system performance with high accuracy.

The Navier-Stokes equations, which describe the conservation of mass, momentum, and energy in fluid flow, are solved using numerical methods to simulate the flow field and temperature distribution within a domain. CFD has become an indispensable tool in various industries, including aerospace, automotive, and energy, for its ability to provide detailed insights into fluid flow and heat transfer processes [14].

2.4.1 Continuity Equation

The continuity equation represents the conservation of mass in a fluid flow. For a general fluid flow, the continuity equation is expressed as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (2.20)$$

where ρ is the fluid density and \mathbf{u} represents the velocity field of the fluid. This equation states that the rate of change of mass within a control volume plus the net mass flux out of the control volume is zero, ensuring the conservation of mass [4]. For a steady, incompressible flow, the fluid density ρ is constant, and the continuity equation simplifies to:

$$\nabla \cdot \mathbf{u} = 0 \quad (2.21)$$

This simplified equation ensures that the volume flow rate into any control volume equals the volume flow rate out, maintaining mass conservation for incompressible fluids [4].

2.4.2 Momentum Equation

The momentum equation, based on Newton's second law, in fluid dynamics is expressed as the Navier-Stokes equation for an incompressible fluid:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{f} \quad (2.22)$$

where ρ is the fluid density, p is the pressure, μ is the dynamic viscosity, and \mathbf{f} represents body forces, such as gravity [11].

2.4.3 Energy Equation

The energy equation in fluid dynamics is used to determine the temperature distribution within the fluid, which is essential for analyzing heat exchange:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) + \Phi \quad (2.23)$$

where T is the temperature, c_p is the specific heat at constant pressure, k is the thermal conductivity, and Φ denotes the viscous dissipation [14, 23].

2.4.4 K-omega Turbulence Model

The K-omega ($k - \omega$) model is a two-equation model that solves two separate transport equations to determine the turbulence kinetic energy (k) and the specific dissipation rate (ω).

The transport equation for the turbulence kinetic energy (k) in the $k - \omega$ SST model is given by:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right] \quad (2.24)$$

The transport equation for the specific dissipation rate ω in the $k - \omega$ SST model is:

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[(\nu + \sigma_\omega \nu_T) \frac{\partial \omega}{\partial x_j} \right] + \frac{2(1 - F_1)}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (2.25)$$

2.4.5 K-epsilon Turbulence Model

The K-epsilon ($k - \epsilon$) model is another popular two-equation model involving the turbulence kinetic energy (k) and the dissipation rate (ϵ).

The transport equation for turbulent kinetic energy (k) is:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k + P_b - \rho \epsilon - Y_M + S_k \quad (2.26)$$

The transport equation for dissipation (ϵ) is:

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (P_k + C_{3\epsilon} P_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \quad (2.27)$$

2.4.6 Wall Treatment and y^+ Values

Both turbulence models require appropriate wall treatment to accurately predict flow behavior near walls. (y^+) is a non-dimensional distance used to determine the adequacy of the near-wall mesh. Lower (y^+) values (typically less than 5) indicate the need for resolving the viscous sublayer, while higher values (30 to 300) are suitable for using wall functions [27].

3

Methodology

One of the goals of the thesis as discussed before, was to automate the whole process of CFD workflow, right from the pre-processing (geometry generation) to post-processing(results and plots) part. This goal was achieved by integrating all the individual scripts that were written for different stages into a unified code using Python.

3.1 Geometry generation

SpaceClaim is a CAD tool integrated into ANSYS, widely used as a geometry cleaning and a pre-processing tool before running a CFD simulation. It also supports basic meshing and scripting capabilities facilitating automation of various tasks within the simulation workflow. Thus the geometries were generated using the Python API built into SpaceClaim. The Python API provides the ability for quick and easy parametric geometry generation. The geometry was first generated by creating an annular section with specified inner and outer arc lengths, which act as the inlet and the outlet of the heat exchanger. In order to generate the desired number of tubes within the annular section, desired mean transverse and longitudinal ratios are fed into the code. The position of the tubes is then calculated using the Python script to ensure that the tubes on each row are staggered. An example geometry could be as shown in figure 3.1.

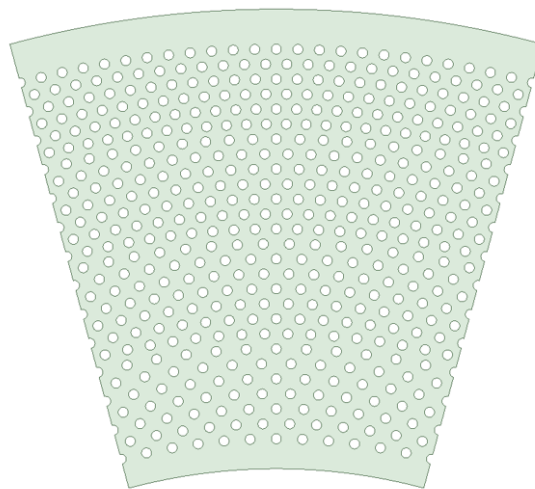


Figure 3.1: Staggered geometry

The code also possesses the function to implement "zones", which are essentially the regions where the number of tubes (which is determined by the transverse ratio) after a certain radius changes. The concept of zoning was inspired by Hugo Petersen GmbH, a German company that introduced the idea for their heat exchanger [10]. This is another variable that has the ability to affect the performance of the heat exchanger. Increasing the number of tubes after a certain radius can affect the heat transfer coefficient and the pressure drop across the heat exchanger. The number of zones is defined by the user and the code automatically generates the geometry based on the zones. This can also be seen implemented in figure 3.2 where as the flow moves from the inlet to the outlet, the number of tubes increases after a certain radius. In this specific case, 4 zones were specified for the geometry

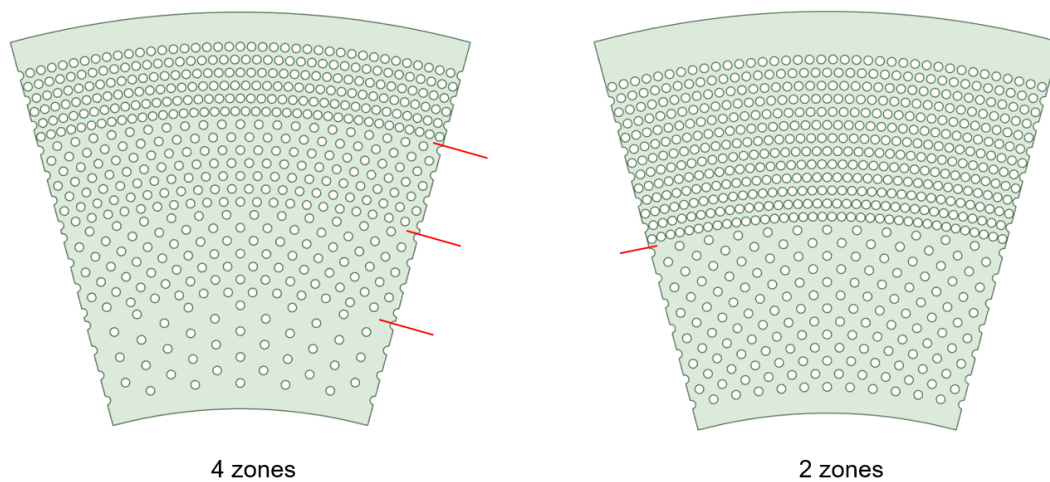


Figure 3.2: Implementation of zones in the geometry

The parameters that were used to generate the geometry are listed in the following table.

Parameter	Value
Tube Diameter	5 mm
Inner Arc radius	0.3 m
Outer Arc radius	0.5 m
Annular section angle	30 degrees
Transverse ratio	1.3 - 3
Longitudinal ratio	1.3 - 2
Number of zones	3 - 4

Table 3.1: Geometry parameters

3.2 Mesh generation

The meshing process of mesh generation followed the geometry generation. Cell size was defined as a function of the tube diameter, e.g, $cellsize = \frac{TubeDiameter}{20}$. Consequently, reducing the tube diameter results in a smaller base cell size, ensuring accurate capture of tube curvature.

In heat transfer simulations, flow separations significantly impact heat transfer across surfaces. To accurately predict separation and capture boundary layer effects, prism layers were adopted on the tube surfaces. A *FirstCellLayerHeight* method is employed, determining the height of the first cell by estimating the maximum Reynolds number expected in the flow domain. It was ensured that the average y^+ value over all the tubes was 1. The maximum y^+ value was anticipated based on the maximum velocity, which was calculated using the concept of the narrowest section outlined in section 2.3.3. The parameters for prism layers were set to -

1. 1st layer height = Corresponding to $y^+=1$
2. Number of layers = 10
3. Growth ratio = 1.2

In order to calculate the first layer height needed for the simulations, the following combination of formulas, as described on CFD online [5], are used -

It is important to know whether or not the Reynolds number is within the laminar or turbulent regime. The Reynolds number is calculated using the formula -

$$Re_D = \frac{\rho u_{max} D}{\mu} \quad (3.1)$$

Where ρ is the density of the fluid, u_{max} is the maximum velocity of the fluid, D is the diameter of the tube and μ is the dynamic viscosity of the fluid.

Once the Reynolds number is calculated, the skin friction coefficient can be calculated using the formula (In this case, Prandtl's law is implemented. There are many other skin friction coefficient calculations that can be used, but for this project, Prandtl's law is used.) -

$$C_f = \frac{0.074}{Re_D^{0.2}} \quad (3.2)$$

Friction velocity is then calculated using the formula -

$$U_\tau = \sqrt{\frac{\tau_w}{\rho}} \quad (3.3)$$

Where τ_w is the wall shear stress. The wall shear stress can be calculated using the formula -

$$\tau_w = \frac{1}{2} \rho u_{max}^2 C_f \quad (3.4)$$

Combining the above formulas, the first layer height can be calculated using the formula -

$$\delta y = \frac{\nu * y^+}{U_\tau} \quad (3.5)$$

While it was feasible to reduce the number of layers to 5, the transition from inflation layers to the base cell size was too abrupt. Adopting 10 layers showed a smaller transition jump, and was therefore deemed more appropriate to ensure smooth transitioning.

3.3 Simulation Setup

3.3.1 Boundary Conditions

The boundary condition data used in this study was based on state-of-the art geared turbofan engine 1000G engine. However, this data was neither provided by Pratt and Whitney nor by GKN. Instead, it was approximately calculated and provided by Chalmers University of Technology. The predicted data included parameters such as pressure, mass flow, and temperature of the exhaust gases after the engine nozzle. The fluid and thermal properties were then calculated using the open-source NASA tool called CEARUN which allows user to input the engine combustion conditions and provide a detailed report consisting of fluid properties such as specific heat, viscosity, conductivity and all the other parameters essential in heat and mass transfer.

Thus, while all engine exhaust conditions i.e the inlet conditions of the heat exchanger were known, the outlet conditions remained unknown. A number of boundary conditions were tried -

1. **Outflow boundary condition** - An outflow condition is commonly applied in CFD simulations when no specific information about exit velocity or pressure is available. It essentially establishes the normal gradients of all variables except pressure as zero, allowing the flow to exit freely. However, this boundary condition is deemed unsuitable for cases involving variable density[1]. Consequently, it was deemed unfit for use and discarded.
2. **Pressure-inlet and mass-flow outlet boundary condition** - This boundary condition was tested, based on the fact that inlet pressure was constant and mass flow out equated mass flow in. However, employing this boundary condition led to unphysical flow characteristics at the outlet and poor convergence.
3. **Pressure-inlet and Targeted Mass flow boundary condition** - Consequently, a pressure-inlet pressure-outlet boundary condition with targeted mass flow was adopted. Here, the flow initialized with a guessed outlet pressure and adjusted itself until the target mass flow was attained. Although this boundary condition exhibited slow convergence, efforts to expedite it by increasing relaxation factors proved minimally effective; surpassing a certain threshold rendered the solution unstable.

Ultimately, the final choice was a mass-flow inlet and pressure-outlet boundary condition without a targeted mass flow condition. An expression was devised for the outlet gauge pressure, enabling it to adjust itself until it aligned with the inlet total pressure of 43250 Pa; a value which corresponded to the engine data provided by Chalmers when the flight is in cruise conditions.

3.3.2 Solver Settings

3.3.2.1 Model

The fluid temperature undergoes continuous changes as it progresses from inlet towards the outlet. Heat exchange occurs as the fluid traverses each row. This exchange of heat causes variations in all the thermophysical properties such as density, specific heat, viscosity and thermal conductivity of the fluid that needs to be accounted for. When carried out a study, these variations were certainly noteworthy in normal cases (up to 25% in case of density) but would be more pronounced in densely packed cases. Therefore, to accommodate these variations, one could employ a piecewise linear function to adjust the fluid properties as a function of temperature. However, rather than implementing this approach for each fluid property individually, a more efficient solution was to utilize the NIST (National Institute of Standards of Technology) model readily available in ANSYS.

The real-gas NIST model consists of database which is calculated using REFPROP. REFPROP is a computer application developed by NIST which provides thermal and physical properties of a variety of fluids for a very wide temperatures and pressures. Hence, all the thermophysical changes that occur during the simulation are accounted using this model.

3.3.2.2 Turbulence Model

The turbulence model employed was the k-omega SST (Shear Stress Transport) model, which combines the strengths of the k-omega and k-epsilon models. This hybrid approach enhances the model's ability to capture near-wall effects and predict boundary layer separation more effectively [16, 17]. The SST model, being a two-equation model, adeptly predicts the transition from laminar to turbulent flow, making it suitable for various flow regimes.

One of the significant advantages of the k-omega SST model is its accuracy in near-wall treatments and low-Reynolds number flows. This accuracy is due to its sensitivity to adverse pressure gradients and its capability to handle low y^+ values without the need for additional damping functions [16]. However, the model can be sensitive to the inlet free-stream values of ω , often requiring fine-tuning of model constants for specific flow configurations [16].

3.3.2.3 Discretisation Schemes and Convergence criteria

The convergence criteria was a combination of monitors and residuals. The residual criteria for all equations which consisted of continuity, momentum, energy, turbu-

lent kinetic energy(k) and specific dissipation rate(w), was set to $1E-6$ which deemed sufficient. Convergence of equations on the other hand does not necessarily mean convergence of the solution. Hence, total pressure drop and heat transfer in the whole domain were used as monitors for convergence.

An observation was made that initializing the solution with the NIST model consistently led to divergence. Consequently, the simulations were initially run for 100 iterations using constant thermophysical properties, allowing them to converge to some extent. The simulations were then halted, and the model was transitioned from constant density real gas to air-NIST, followed by an additional 1000 iterations alongside other convergence monitors

Following are the boundary conditions and simulation setup summarised -

Models	Steady Fluid/Gas model - NIST Coupled flow Turbulence Model - k-Omega SST
Discretization scheme	2nd Order upwind - X and Y Momentum, k, w, energy
Inlet conditions	Mass flow in = 0.87423 kg/s Temperature = 661.1338 K Density = 0.2279 kg/m ³ Viscosity = 3.2e-5 Pa.s Thermal Conductivity = 0.0487 W/mK
Outlet	Pressure = <i>Custom expression</i>
Tubes	Temperature = 300 K No slip wall
Side walls	Periodic 1 and Periodic 2
Stopping criteria (1000 iterations)	Continuity residual minimum value: 1E-6 X-momentum convergence criteria: 1E-6 Y-momentum convergence criteria: 1E-6 Energy convergence criteria: 1E-6 OR Monitored Total pressure drop: 1E-3 Monitored Total Heat transfer: 1E-3

Table 3.2: Boundary conditions and Simulation setup in ANSYS FLUENT

3.4 Post-processing

In order to accurately predict the Nusselt number, it is crucial to precisely estimate the heat transfer coefficient (HTC). Achieving accurate HTC calculation depends upon assuming the correct bulk temperature T_{bulk} in (2.1).

For a single cylinder scenario, the bulk temperature coincides with the fluid's inlet temperature. Thus, when conducting a CFD study involving only one tube or a single row of cylinders, it's generally safe to consider the bulk temperature as the inlet temperature of the fluid. However, this assumption doesn't hold true for multiple rows of cylinders. In such cases, as discussed above in section 3.3.2.1, the fluid temperature undergoes continuous changes as it progresses toward the outlet. To address these changes, multiple sections were constructed at constant radii between the tube rows. The bulk temperature for a tube row was then determined as the mass flow-averaged temperature across the preceding tube row section 3.3.

Zukauskas correlations accommodate these variations through the $(Pr/Pr_{wall})^{0.25}$ term in equation (2.7), as well as by utilizing mean fluid properties such as density $(\rho_{in} + \rho_{out}/2)$ in pressure correlations.

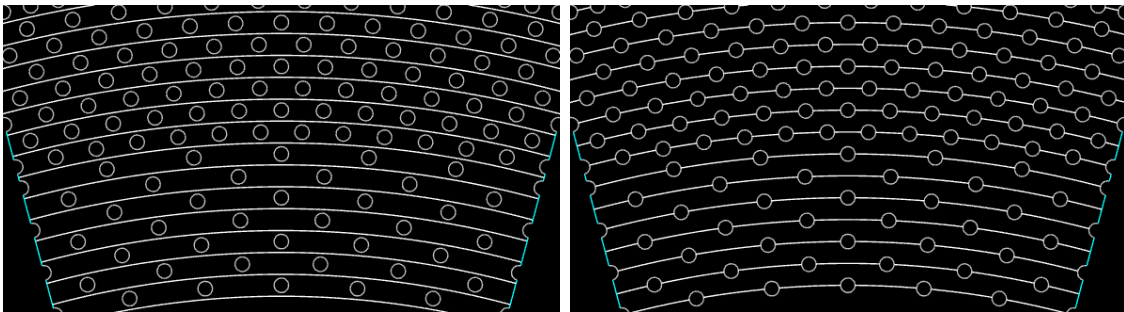


Figure 3.3: Bulk temperature sections **Figure 3.4:** Bulk velocity sections

A similar approach was adopted to calculate the Reynolds number (and consequently the maximum Reynolds number) across the entire tube bank. Instead of considering the sections between two tube rows, sections were constructed along the tube rows 3.4. This adjustment was implemented to ensure that the maximum Reynolds number closely corresponds to the one calculated using the concept of the narrowest region. Hence, area-averaged velocities, as well as mass-averaged densities and viscosities, were computed at the tube row sections.

In addition to conventional velocity and temperature contour plots, multiple report definitions and plots were defined such as *mass flow outlet*, *pressure losses*, *mass averaged - densities*, *temperature*, *specific heat*, *conductivity*, *total heat transfer* were written out and plotted in order to monitor convergence as well as to calculate and compare with the analytical relations.

3.5 Test Matrix

In order to get a better understanding of the effect of the different parameters on the heat transfer coefficient and pressure drop, a test matrix was created. The parameters that were varied were the transverse ratio, longitudinal ratio and the number of zones. The average transverse ratio of the domain was varied from 1.25 to 3, the average longitudinal ratio of the domain was also varied from 1.25 to 2. All

of the following tests were carried out with 3 and 4 zones. The reason for choosing 3 and 4 zones for the test matrix was that the starting st values for 1 and 2 zones were too small for any average transverse ratio less than 1.6, leading to problems with the meshing process. This would not allow for a large enough test matrix and therefore not provide a good comparison between the different average transverse ratios. The varying transverse ratios were done for an average of 1.6 to 2 since values lower than that won't allow for much variability in the zones, and for that reason, were not included in the test matrix.

The test matrix is as follows -

3 Zones			
Average Domain Sl/D	St Per Zone (Constant St/D)	St Per Zone (Varying St/D)	Average Domain St/D
1.25	1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6	2, 1.5, 1.3	1.6
	1.8, 1.8, 1.8	2.3, 1.8, 1.3	1.8
	2.0, 2.0, 2.0	2.7, 2, 1.3	2.0
1.5	1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6	2, 1.5, 1.3	1.6
	1.8, 1.8, 1.8	2.3, 1.8, 1.3	1.8
	2.0, 2.0, 2.0	2.7, 2, 1.3	2.0
1.75	1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6	2, 1.5, 1.3	1.6
	1.8, 1.8, 1.8	2.3, 1.8, 1.3	1.8
	2.0, 2.0, 2.0	2.7, 2, 1.3	2.0
2	1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6	2, 1.5, 1.3	1.6
	1.8, 1.8, 1.8	2.3, 1.8, 1.3	1.8
	2.0, 2.0, 2.0	2.7, 2, 1.3	2.0
4 Zones			
Average Domain Sl/D	St Per Zone (Constant St/D)	St Per Zone (Varying St/D)	Average Domain St/D
1.25	1.3, 1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6, 1.6	2, 1.7, 1.4, 1.3	1.6
	1.8, 1.8, 1.8, 1.8	2.5, 1.8, 1.6, 1.3	1.8
	2.0, 2.0, 2.0, 2.0	3, 2, 1.7, 1.3	2.0
1.5	1.3, 1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6, 1.6	2, 1.7, 1.4, 1.3	1.6
	1.8, 1.8, 1.8, 1.8	2.5, 1.8, 1.6, 1.3	1.8
	2.0, 2.0, 2.0, 2.0	3, 2, 1.7, 1.3	2.0
1.75	1.3, 1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6, 1.6	2, 1.7, 1.4, 1.3	1.6
	1.8, 1.8, 1.8, 1.8	2.5, 1.8, 1.6, 1.3	1.8
	2.0, 2.0, 2.0, 2.0	3, 2, 1.7, 1.3	2.0
2	1.3, 1.3, 1.3, 1.3		1.3
	1.4, 1.4, 1.4, 1.4		1.4
	1.6, 1.6, 1.6, 1.6	2, 1.7, 1.4, 1.3	1.6
	1.8, 1.8, 1.8, 1.8	2.5, 1.8, 1.6, 1.3	1.8
	2.0, 2.0, 2.0, 2.0	3, 2, 1.7, 1.3	2.0

Table 3.3: Test Matrix

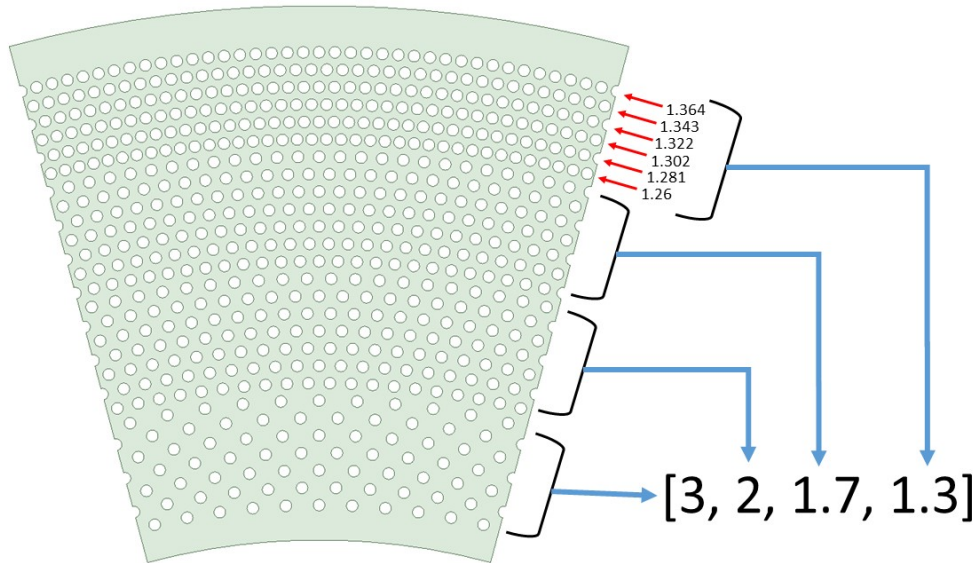


Figure 3.5: A case depicting the calculation of average St/D ratio for a zone.

What the St/D values [2,2,2,2] represent here is that the average St/D ratio of the first zone is 2, the average St/D ratio of the second zone is 2, and so forth.

As the radial distance increases, the length of the arc also increases. Therefore, to maintain a consistent pitch throughout the entire section, additional tubes must be added. However, this would disrupt the staggered arrangement between rows. To preserve the staggered arrangement, the number of tubes must remain constant, allowing for manipulation of the St/D ratio.

Therefore, the average St/D ratio for each zone was defined as the average of the St/D ratios of all the rows within that section. For example, for a case with average St/D ratio of 1.3 for the last section, the St/D ratio of all the other rows in that section were calculated using a script and set in such a way that the average of them would turn out to be 1.3 (fig. 3.5).

Two types of arrangements were explored in this study – constant and variable zoning. In a constant zoning case, the St/D ratio of all the zones would be the same, for example [2,2,2,2]. In contrast, variable zoning meant that the St/D ratio for each zone would be different. For example, a variable zoning case corresponding to a constant zoning case [2,2,2,2] could be [3,2,1.7,1.3], where the average St/D ratio for the entire heat exchanger would still be 2 (calculated $3 + 2 + 1.7 + 1.3$ divided by 4)

3.6 Correlation Validation

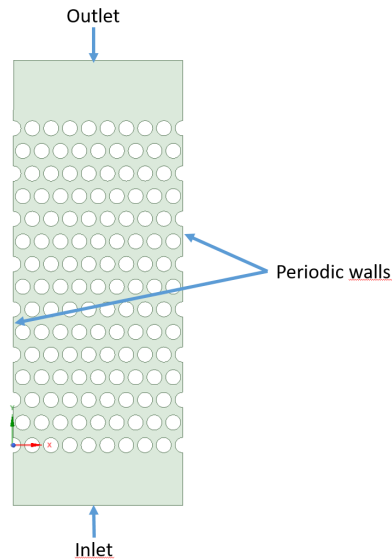


Figure 3.6: A rectangular domain constant $Sl/D = 1.5$ and $St/D = 1.25$

In order to know whether or not the CFD model employed functions as expected, it is crucial to validate the results obtained from the CFD model with analytical relations. The geometry consisted of a rectangular domain with constant longitudinal and transverse ratios along said domain. An example of such a geometry is shown in figure 3.6. The Nusselt number and Pressure drop were calculated using the Zukauskas correlation equations that were presented in equations (2.8) and (2.14) respectively. They were then compared to the CFD results to see how far off the CFD model was from the analytical relations. The results were then plotted to see how well the CFD model was able to predict the heat transfer coefficient and pressure drop. The test matrix for the correlation validation was as follows:

Longitudinal Pitch Ratio	Transverse Pitch Ratio
0.9	1.5
1.0	1.5
1.25	1.5
1.5	1.5
1.75	1.5
1.5	1.75
1.5	1.25

3.7 Mesh Independence Study

In order to ensure that the mesh was independent of the results, a mesh independence study was conducted. The mesh was refined by changing the cell size and the

first layer cell height by a factor of 2. This was done to see how sensitive the solution is to mesh refinement. The parameters for different cases could be found below in 3.5

Case	Cell size	1st layer cell height corresponding to	Mesh Count
Case 1	TubeDiameter/5	$y^+ = 4$	120k
Case 2	TubeDiameter/10	$y^+ = 2$	340k
Case 3	TubeDiameter/20	$y^+ = 1$	1.1 million
Case 4	TubeDiameter/40	$y^+ = 0.5$	3 million

Table 3.5: Mesh Parameters for every case

The geometry selected for the mesh convergence study was carefully selected to incorporate a blend of low and high St values. This selection was made with a rough concept of how the most optimized case (yielding the highest HT/dP) might appear. Consequently, the number of zones was constrained to four, with St values as [6, 3, 2, 1.5] corresponding to each zone.

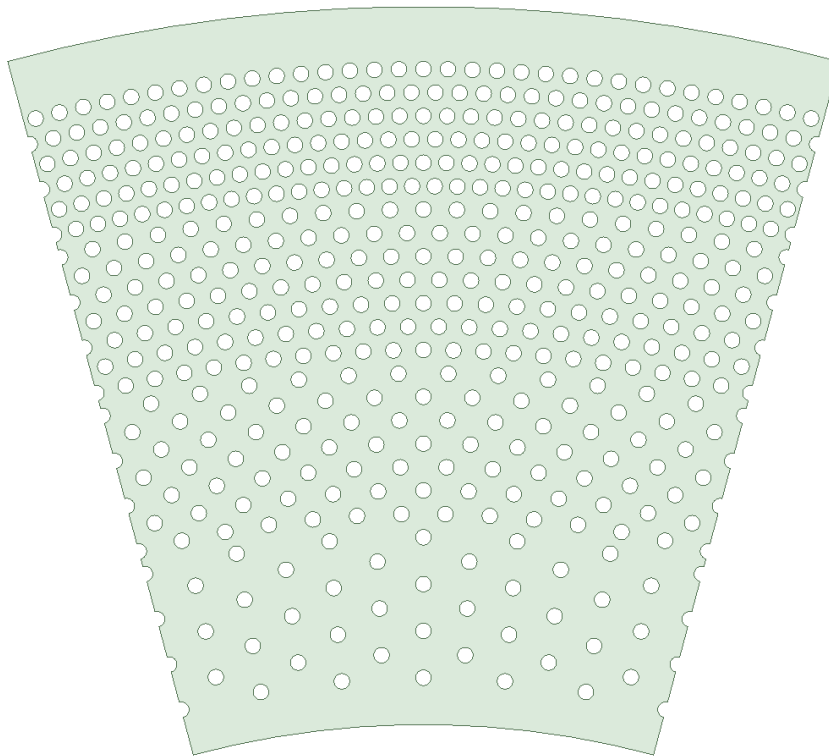


Figure 3.7: Geometry of Mesh independence studies

4

Results and Discussion

This chapter presents the results obtained from the simulations in the form of tables and plots. It further discusses how different tube arrangement designs affect the performance of the heat exchanger. By analyzing these results, we aim to understand the impact of various configurations mainly on overall performance and performance per tube. The overall performance is calculated by dividing the total heat transfer by the total pressure drop (HT/dP), while performance per tube is calculated as the overall performance divided by the total number of tubes (HT/dP per tube). Hence, the unit [W/Pa] remains the same, just that performance per tube is a scaled value proportion to the number of tubes giving an indicative performance with respect to the weight of the heat exchanger.

4.1 Mesh Independence Study Results

The simulation was setup as discussed in table 3.5 and simulations were run until the custom made monitors - total heat transfer and pressure drop over the whole heat exchanger, no longer fluctuated. Table 4.1 below comprises the final converged values of all the 4 cases. It was decided to proceed with the mesh settings of Case 3. Further details and reasoning are discussed in subsequent section.

Case	Cell size	Nusselt Number	HT/dP
Case 1	TubeDiameter/5	24.983	286.41
Case 2	TubeDiameter/10	23.535	313.54
Case 3	TubeDiameter/20	22.95	318.19
Case 4	TubeDiameter/40	22.697	319.56

Table 4.1: Total heat transfer and pressure drop values for all the cases

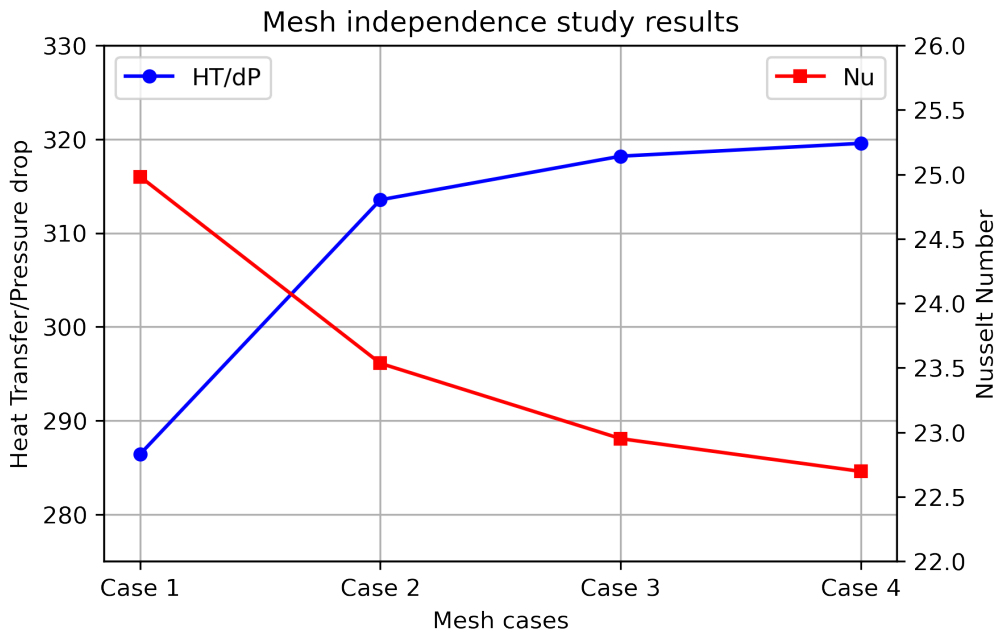


Figure 4.1: Mesh independence study results

The difference in total HT/dP ratio and Nusselt number between Case 4 and Case 3 was minimal, at just 0.5% and 1.1% respectively, indicating satisfactory mesh convergence. However, an attempt was made with more refined mesh settings for Case 5, aiming for higher precision. However, this attempt proved unsuccessful as SpaceClaim took extended amount of time struggling to handle the higher mesh count, ultimately leading to a program crash. Given the considerable computational and time investment required for Case 4 mesh settings for a marginal improvement in accuracy, it was decided to proceed with the mesh settings of Case 3.

4.2 Correlation Validation

Although the mesh independence study was carried out for annular section, it was decided to use the same mesh settings for the rectangular domain with constant longitudinal and transverse pitches. The study was also conducted with an equal number of tubes in every scenario, which means a constant total area for heat transfer. Thus, one way to interpret the results would be how efficient is the arrangement is in terms of performance of heat exchanger.

The inlet conditions were kept same across all cases to ensure that the Reynolds number fell within the range of 2000-3000, consistent with the operational range of our annular heat exchanger. The correlation was then validated by comparing the results from the CFD simulations with the Zukauskas correlation. The Zukauskas Nusselt number and pressure drop were calculated using a Python library called 'ht', which encompasses various heat transfer modules used for design calculations of boilers, heat exchangers, radiative heat transfer, and many other applications[8].

The validation was done by comparing the Reynolds number, heat transfer, Nusselt number, and pressure drop for different values of the Sl/D and St/D ratios. The results are presented in the following figures and tables.

Sl/D	CFD Nu.	CFD dP [Pa]	Zuk. Nu.	Zuk. dP	Nu Dev %	dP Dev %
0.9	33.169	477.776	36.536	418.418	9.22	-14.19
1.0	26.325	234.718	31.282	306.869	15.85	23.48
1.25	26.769	241.25	29.641	286.669	9.69	15.84
1.5	26.994	241.825	27.67	283.555	2.44	14.72
1.75	26.889	244.131	27.626	279.382	2.67	12.62

Table 4.2: Zukasukas Nu and dP Deviation for varying Sl/D and constant St/D=1.5

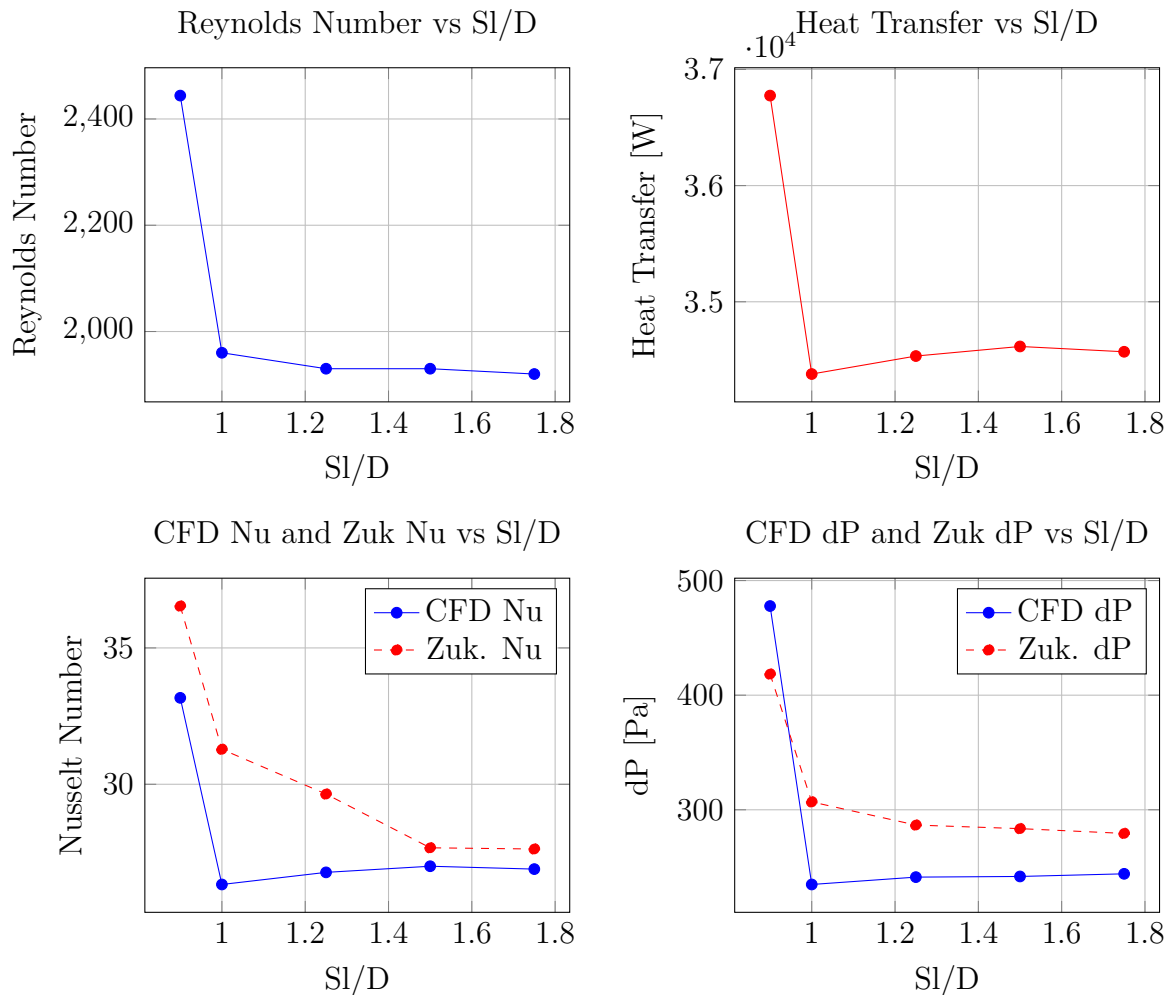


Figure 4.2: Correlation Validation with Constant St/D=1.5

Figure 4.2 and table 4.2 show the results for varying the Sl/D ratio with a constant St/D ratio, while figure 4.3 and table 4.3 show the results for varying the St/D ratio while keeping the Sl/D ratio constant.

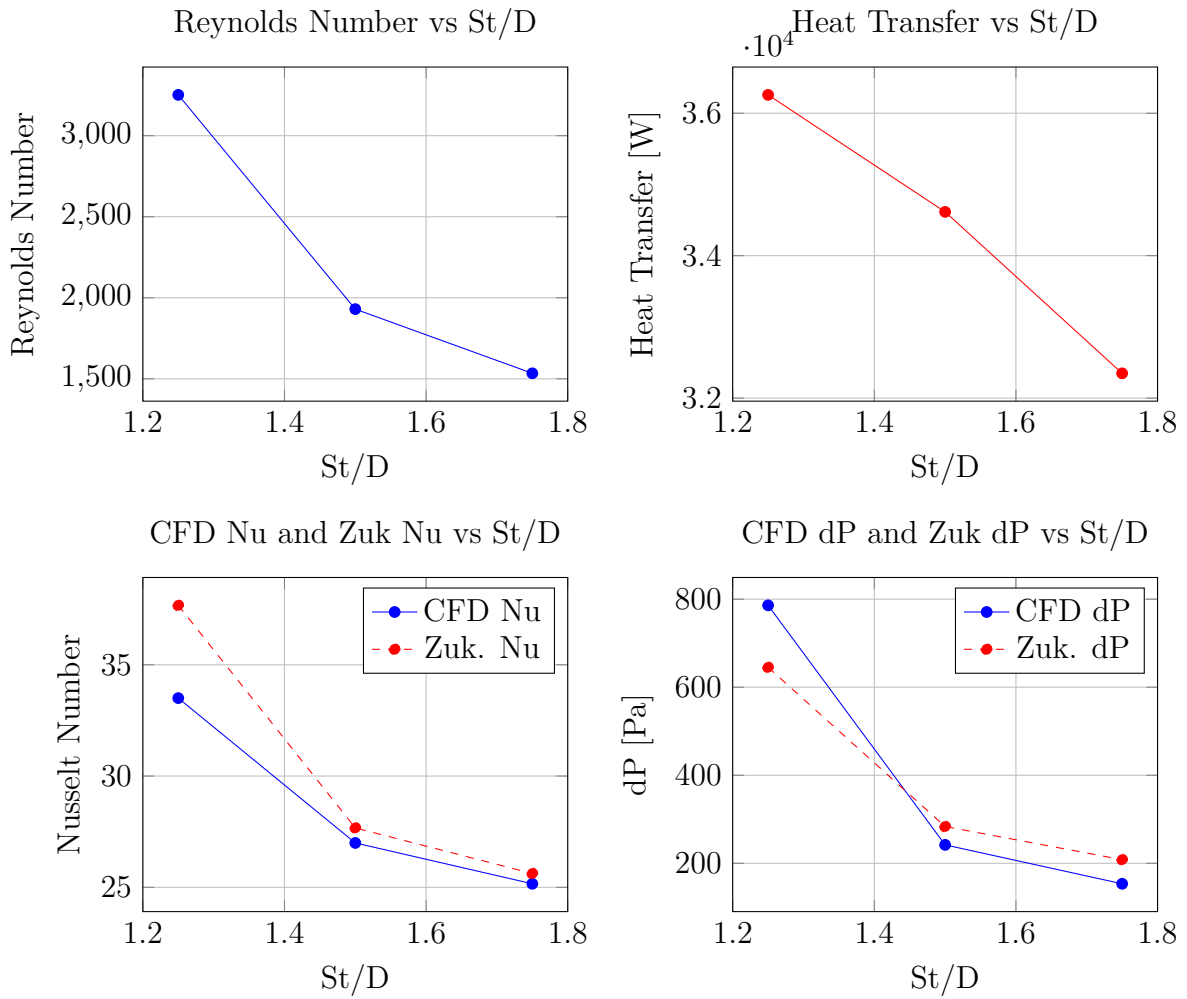


Figure 4.3: Correlation Validation with Constant $Sl/D=1.5$

St/D	CFD Nu.	CFD dP [Pa]	Zuk. Nu.	Zuk. dP	Nu dev %	dP dev %
1.25	25.159	153.480	25.621	208.269	1.80	26.31
1.5	26.994	241.825	27.67	283.555	2.44	14.72
1.75	33.052	785.96	37.672	645.141	12.26	-21.83

Table 4.3: Zukasukas Nu and dP Deviation for varying St/D and constant $Sl/D=1.5$

The theory of the critical Sl/D ratio (derived from concept of narrowest region), which leads to a sudden increase in heat transfer and pressure drop, was also observed when the Sl/D ratio was set to 0.9 in figure 4.2. This suggests that it is more advantageous to stack or pack the tubes in the longitudinal (vertical) direction rather than in the normal (horizontal) direction of the flow. Thus, a significant reduction in the volume of the heat exchanger can be achieved for a marginal reduction in performance.

The Nusselt number deviations were consistently low in almost all cases. However, higher deviations were observed in cases with low Sl/D and St/D ratios. These errors

may be due to mesh issues, suggesting that more cells might be needed between two tubes when they are close to each other for accurate results.

The literature indicates that Zukauskas correlations tend to significantly over-predict pressure drop. For instance, sources like Beale and Spalding [3] also report poor agreements with the experimental data in general. However, the pressure drop showed very high deviations in some cases, reaching up to 26%. The reason for this discrepancy might be that CFD simulations account for the effect of varying thermodynamic properties after each tube row section. In contrast, the Zukauskas correlation does not consider these effects when calculating the pressure drop. Additionally, the correction factors all the tube arrangements and different Reynolds numbers are not readily available. Therefore, the 'ht' module employs a complex curve or spline fitting method to estimate these unknown points. Consequently, higher errors are reasonable under those design conditions where correction factors are not perhaps readily available.

4.3 Results for an example case

Fig.4.4 and fig.4.5 lay out various contour and plots representing a case with $Sl/D = 1.5$ and $St/D = [1.6,1.6,1.6,1.6]$ as an illustrative example.

The contour plots, generated in Fluent, were utilized to analyze the overall flow behavior and variations in thermophysical properties as the fluid progresses through the tube arrangement. As the flow traverses outward and cools down, there's a reduction in fluid volume, resulting in an increase in density. This trend is illustrated in figures 4.4(c) and 4.4(d). Additionally, velocity and pressure contours, depicted in figures 4.4(a) and 4.4(b), were examined to identify any interesting or abnormal behavior of flow characteristics within the domain such as misaligned flow illustrated in fig. 4.4(a) in which the flow tends to flow in a certain direction(left in this case) instead of radially-normally outward.

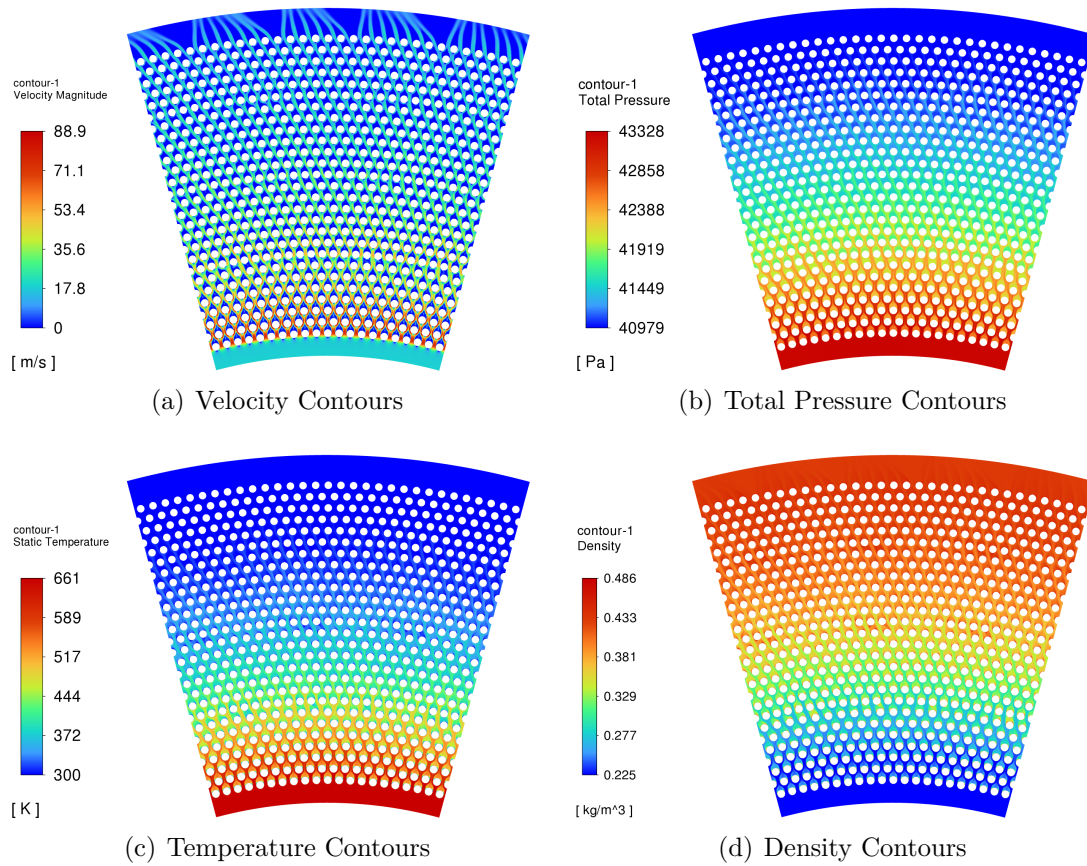


Figure 4.4: Contours obtained from Fluent for all the simulations

In the example case with a longitudinal ratio of 1.5 and an average transverse ratio of 1.6 across 4 zones, multiple subsections were established between the tube row sections to calculate the average thermal properties of the fluid at each section. Figure 4.5(a) shows how the number of tubes increases in each zone to maintain a transverse pitch ratio of 1.6, with red dashed lines indicating the points where new tubes are added or a new zone begins. Figures 4.5(b) illustrate how the radial expansion of the flow area leads to a decrease in velocity (see Fig. 4.5(c)) and Reynolds number (Fig. 4.5(d)).

As depicted in Figure 4.5(e), the pressure drop decreases gradually for each row section as the flow moves radially outward, directly related to velocity (see correlation 2.14). The addition of a new zone results in a spike in pressure losses due to increased velocity.

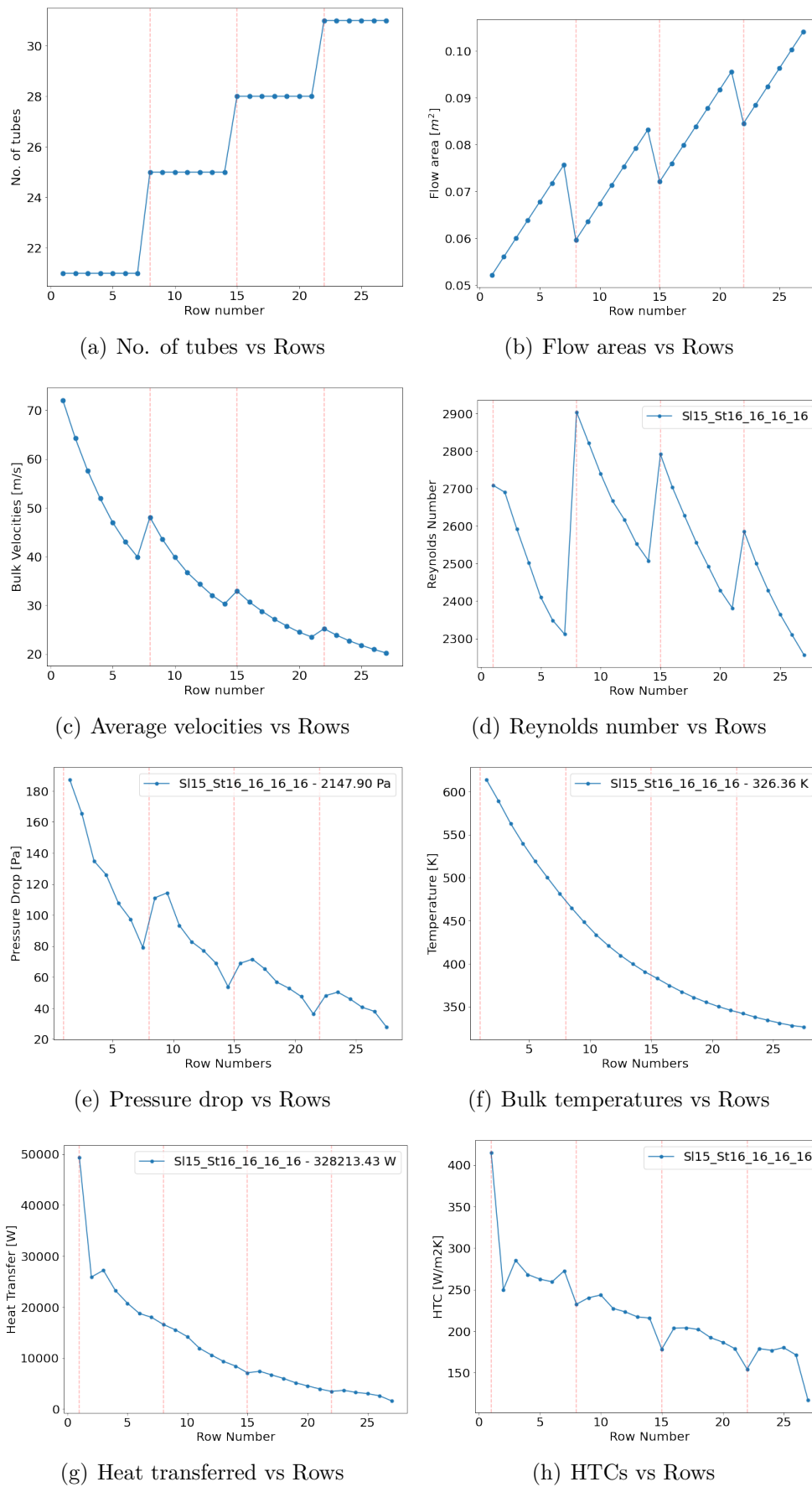


Figure 4.5: Plots for example case with $Sl/D=1.5$ and $St/D=[1.6,1.6,1.6,1.6]$

Figure 4.5(f) shows the temperature progression behind each tube row section from the inlet to the outlet. Meanwhile, Figure 4.5(h) demonstrates a notable decline in the heat transfer coefficient (HTC) with the introduction of a new zone, as some of the newer tubes fall behind those of the previous row. The second row section experiences higher pressure drops than the first, regaining its staggered arrangement, with pressure drop spikes when new tubes are added (rows 8, 15, and 22) and higher drops in the second rows after the zone change (rows 9, 16, and 23).

If the cooling demand were lower, with an average outlet temperature of 350K or 400K instead of 300K (wall temperature), the heat exchanger would require fewer rows to meet the cooling demand, reducing the volume and weight of the heat exchanger, resulting in higher tube performance.

4.4 Effect of varying St/D

To better understand how the St/D for a constant Sl/D affected performance, the results were plotted for different St/D values for a constant Sl/D . Figures 4.6 and 4.7 show the general trends lines for cases with the same Sl/D ($Sl/D=1.25$ and $Sl/D=2$) respectively.

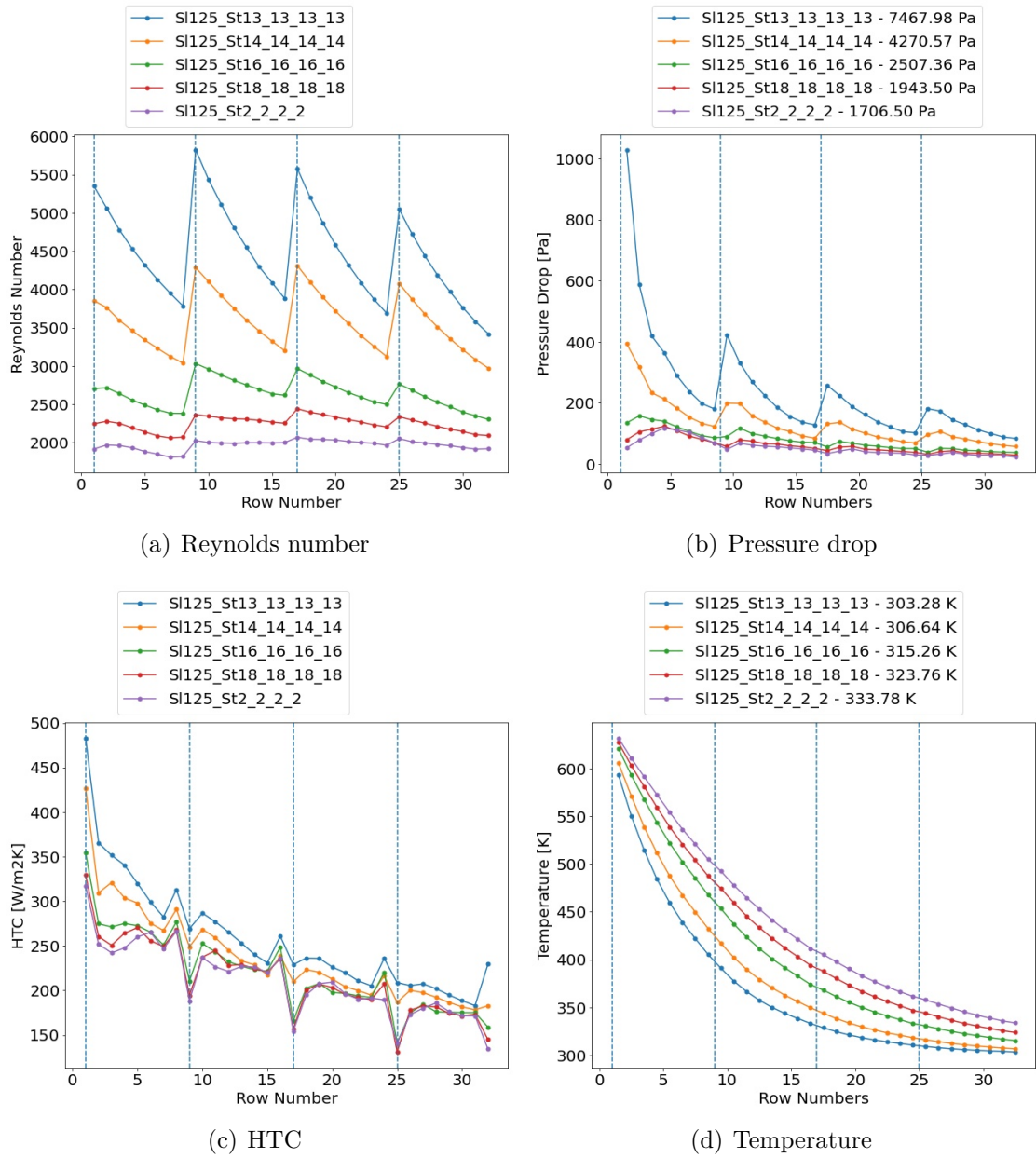


Figure 4.6: Varying St/D for constant Sl/D = 1.25

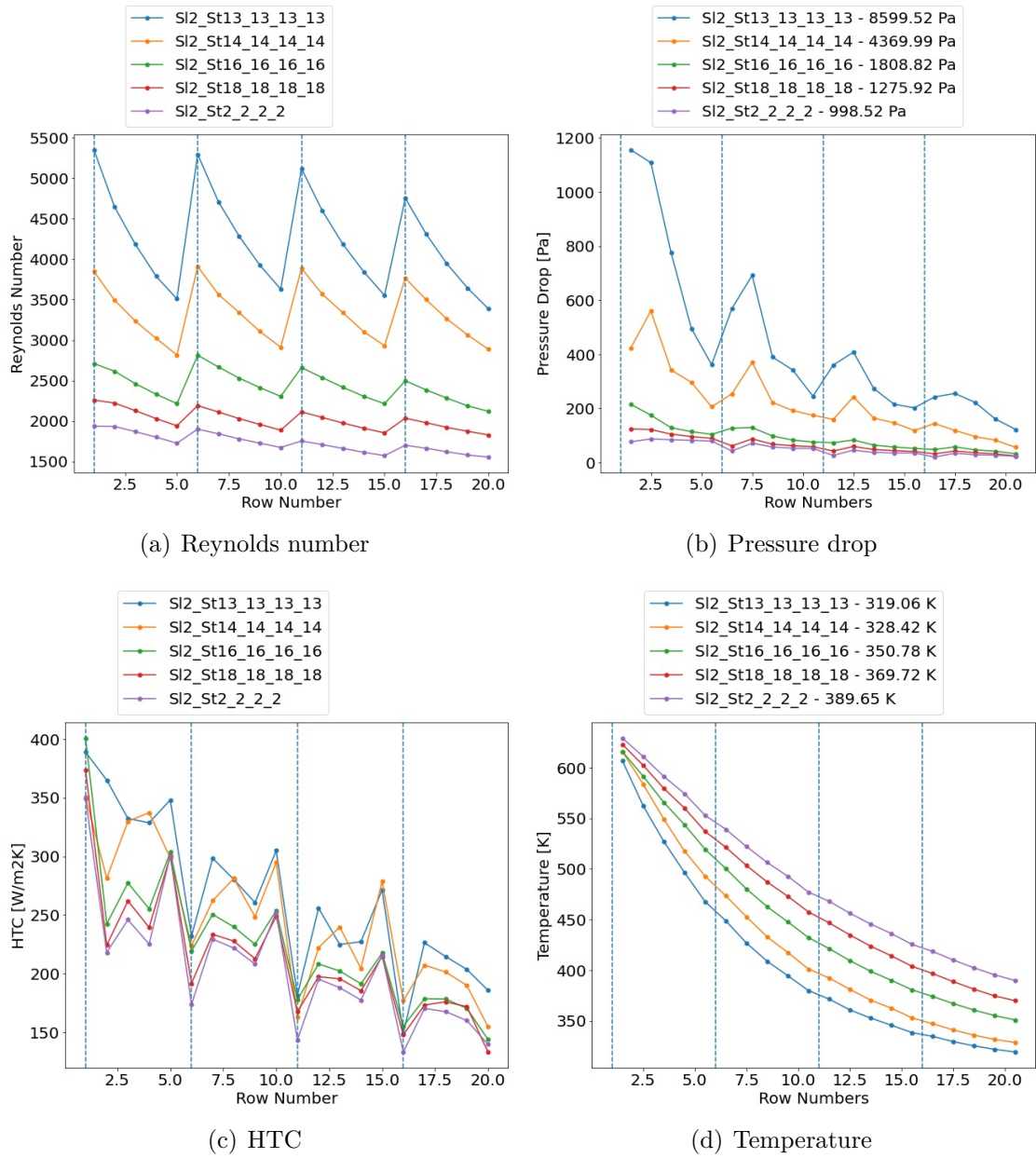


Figure 4.7: Varying St/D for constant $Sl/D = 2$

Figure 4.8 illustrates how the performance parameter, HT/dP , varies with St/D ratio as Sl/D is kept constant.

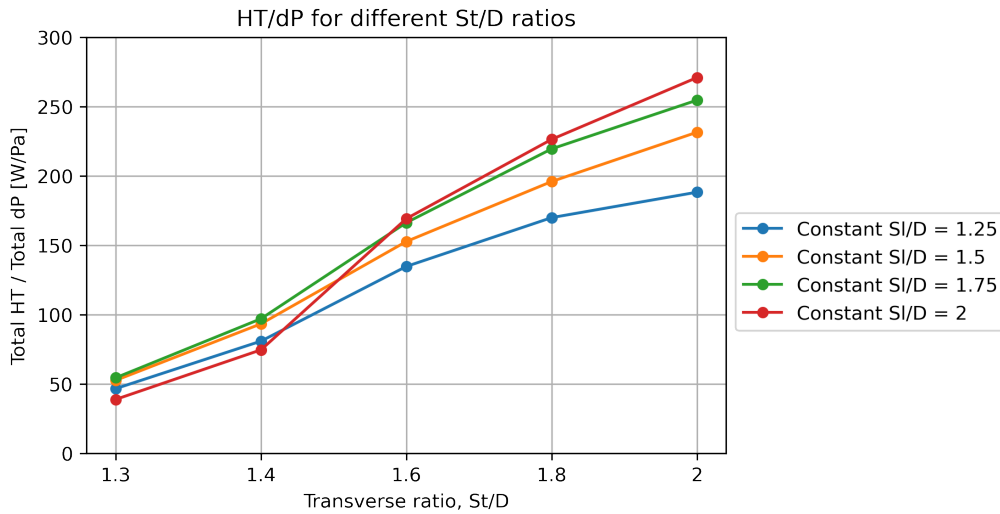


Figure 4.8: Constant zonewise Sl/D vs varying St/D

The transverse pitch ratio significantly impacts heat exchanger performance. As the St/D ratio decreases, the heat transfer rate increases, as seen in figures 4.6 and 4.7, but so does the pressure drop. This occurs because decreasing the St/D ratio allows more tubes to fit within the same arc length, thereby increasing the heat transfer area. This leads to an increase in total heat transfer. Additionally, the velocity between two tubes increases as the cross-sectional area through which the fluid must pass decreases. This results in higher pressure losses.

4.5 Effect of varying Sl/D

To better understand how the Sl/D for a constant St/D affected performance, the results were plotted for different Sl/D values. Figures 4.9 and 4.10 show the general trends lines for cases with the same St/D (St/D=2 and St/D=1.3 respectively).

As the Sl/D ratio increases, fewer rows can fit inside the section. Consequently, each case had a different number of rows, making it challenging for readers to distinguish the performance parameter trends when plotted against the number of rows. Therefore, it was decided to plot the performance parameters against the radial distance instead.

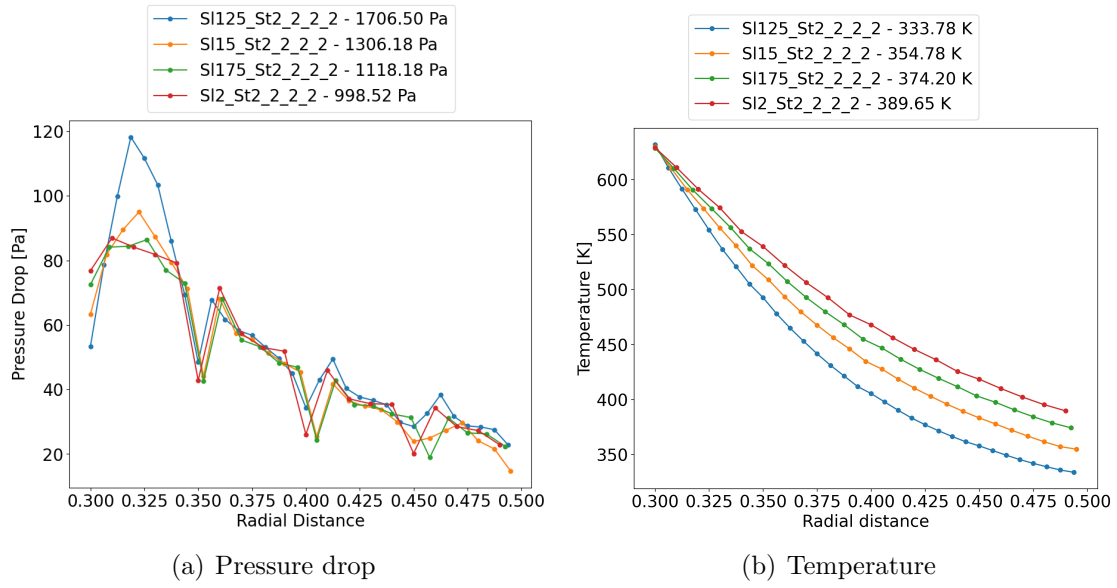


Figure 4.9: Constant St/D vs Varying Sl/D for scarcely packed case

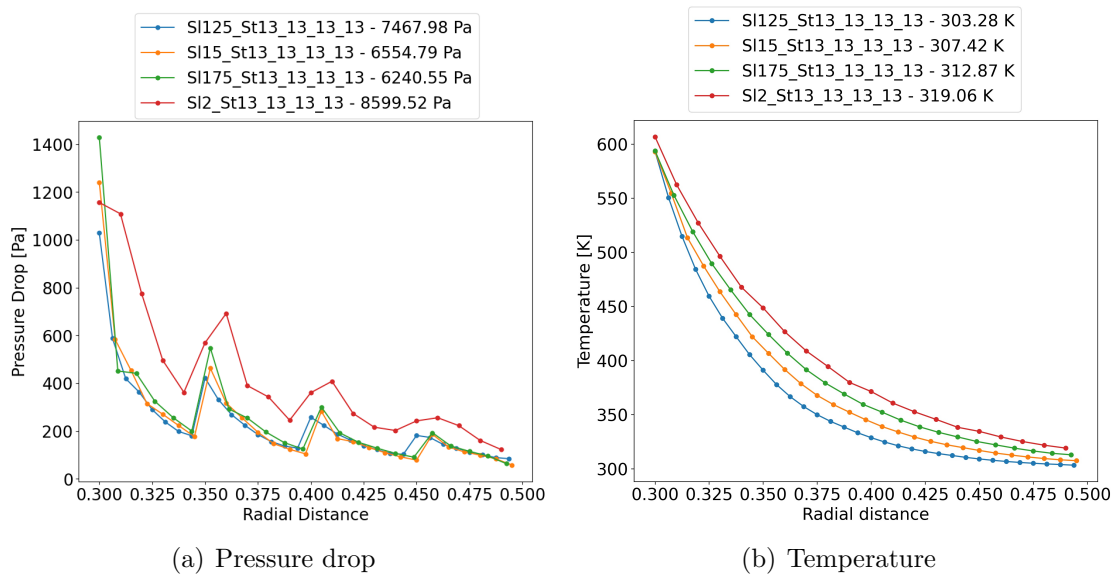


Figure 4.10: Constant St/D vs Varying Sl/D for densely packed case

Figure 4.11 illustrates how the performance parameter, HT/dP , varies with Sl/D ratio as St/D is kept constant.

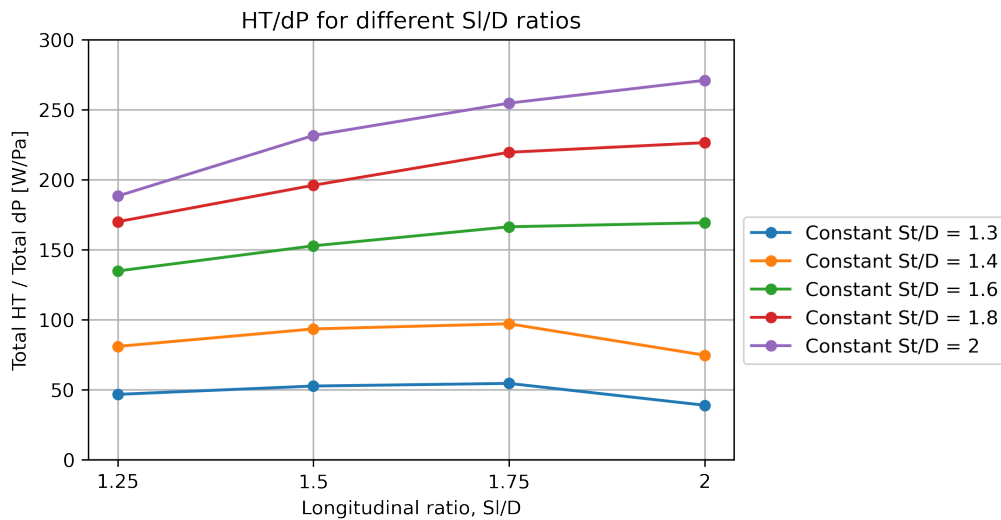


Figure 4.11: Constant zonewise St/D vs varying Sl/D

The longitudinal pitch ratio significantly also impacts heat exchanger performance. As the Sl/D ratio decreases, the heat transfer rate increases, as seen in fig. 4.9(b) and tables 4.4 and 4.5, but so does the pressure drop. This is because decreasing the Sl/D ratio allows more tube row sections to be stacked within the same volume, resulting in higher heat transfer and pressure drop.

The heat transfer-to-pressure drop ratio is higher in configurations with a higher Sl/D ratio for the same St/D , indicating that heat can be exchanged more efficiently with lesser pressure losses. This makes higher Sl/D values more preferable for a more efficient heat exchange if volume constraints are not significant. Additionally, configurations with higher St/D and Sl/D values yield higher HT/dP ratios, as shown in 4.11, meaning more heat can be exchanged for lesser pressure losses.

However, using the highest St/D and Sl/D values doesn't necessarily mean that the heat load would be satisfied. It only means heat can be exchanged more efficiently. If the heat load needs to be satisfied, then one needs to start decreasing the pitch values gradually until the heat transfer demand is met.

4.6 Constant zoning vs. Variable zoning

The results of the comparison between constant and variable zoning are presented in tables 4.4, and 4.5. The tables compare the heat transfer, pressure drop, outlet temperature, overall performance and performance per tube for each case. The results show that the constant zoning approach outperforms the variable zoning approach in terms of heat transfer per pressure drop.

		Cases	Heat Transfer [W]	Pressure drop [Pa]	Outlet Temp. [K]	HT/dP [W/Pa]	Number of tubes	Performance per tube [W/Pa]
3 Zones	Average St/D 1.6	Average Si/D 1.25	339282.6568	2595.830167	313.9061115	130.70295	869	0.150406155
		St2_15_13	343781.02	3425.91	308.89	100.34736	913	0.109909484
		Average Si/D 1.5	328831.4721	2224.322692	325.670343	147.83443	711	0.207924652
		St2_15_13	336482.53	3056.38	317.14	110.09185	747	0.147378649
		Average Si/D 1.75	317169.9494	2003.935115	338.660255	158.27356	601	0.263350353
		St2_15_13	326301.62	2581.5	328.52	126.40001	626	0.201916945
	Average St/D 1.8	Average Si/D 2	306289.3169	1861.007202	350.6944596	164.58255	522	0.315292248
		St2_15_13	315934.74	2736.68	340.04	115.44453	543	0.21260503
		Average Si/D 1.25	330681.0357	1931.179175	323.5143844	171.23271	759	0.225603038
		St23_18_13	339801.2104	3128.844532	313.3628094	108.60278	836	0.12990763
		Average Si/D 1.5	313992.1971	1553.175056	342.1351001	202.1615	621	0.325541866
		St23_18_13	330200.7916	2642.291232	324.1445885	124.9676	684	0.182701168
Average St/D 2	Average Si/D 1.75	298330.9101	1337.948692	359.4301183	222.97635	525	0.424716849	
	St23_18_13	316962.7355	2156.427224	338.8798733	146.98513	570	0.257868649	
	Average Si/D 2	284676.0361	1226.883115	374.3831184	232.03191	456	0.508841914	
	St23_18_13	303665.8786	2338.715823	353.5801642	129.843	494	0.262840081	
	Average Si/D 1.25	322240.2863	1732.774967	332.913888	185.96776	682	0.272680006	
	St27_2_13	337473.0614	2962.036602	315.974759	113.93278	792	0.143854519	
	Average Si/D 1.5	301181.5284	1289.683111	356.254979	233.53142	558	0.41851509	
	St27_2_13	326726.4046	2575.226477	328.0163678	126.87288	648	0.195791484	
	Average Si/D 1.75	284053.3629	1120.993835	375.0516393	253.39422	472	0.536852169	
	St27_2_13	311888.588	2055.920658	344.4924633	151.70264	538	0.281975164	
	Average Si/D 2	267754.7142	992.5559512	392.7533483	269.76284	410	0.657958151	
	St27_2_13	297994.4138	2265.775265	359.8133763	131.51985	466	0.282231429	

Table 4.4: Comparing Performance Parameters of Varying vs Constant St/D per Zone for 3 Zones

	Cases	Heat Transfer [W]	Pressure drop [Pa]	Outlet Temp. [K]	HT/ ρP [W/Pa]	Number of tubes	Performance per tube [W/Pa]
Average St/D 1.6	Average Sl/D 1.25	338073.3657	2507.363637	315.2643181	134.8322	840	0.160514529
		342307.6014	3065.496831	310.545411	111.66464	880	0.126891637
	Average Sl/D 1.5	328213.4327	2147.900713	326.3582103	152.80661	704	0.217054848
		333493.1526	2384.500794	320.4742082	139.85869	732	0.191063781
	Average Sl/D 1.75	316059.5644	1899.341538	339.8880248	166.40481	599	0.277804354
		323794.1879	2176.80639	331.3054674	148.74735	622	0.239143654
	Average Sl/D 2	306212.5766	1808.824479	350.7786632	169.28816	525	0.322453647
		316224.0195	2741.614095	339.7168447	115.34228	550	0.209713236
	Average Sl/D 1.25	330462.3847	1943.502976	323.7570281	170.03441	752	0.22610959
		337687.5641	2687.739821	315.730775	125.63998	816	0.153970558
	Average Sl/D 1.5	315470.9615	1609.069277	340.4995986	196.05804	630	0.311203231
		326355.5742	1977.131929	328.4244755	165.06515	676	0.244179213
Average St/D 1.8	Average Sl/D 1.75	301090.5303	1370.993521	356.3992095	219.61485	536	0.409729189
		314215.7641	1746.977598	341.9187127	179.8625	574	0.313349309
	Average Sl/D 2	288953.1863	1275.92005	369.7163223	226.46653	470	0.481843681
		305943.7179	2008.027016	351.0692915	152.36036	510	0.298745803
	Average Sl/D 1.25	321460.5759	1706.504474	333.7809368	188.37371	672	0.280318018
		333218.3337	2186.871809	320.7433633	152.37214	760	0.200489656
	Average Sl/D 1.5	302530.0512	1306.182981	354.7760077	231.61384	563	0.411392249
		319731.0662	1728.701257	335.7857935	184.95449	627	0.294983244
	Average Sl/D 1.75	284838.8742	1118.178349	374.1955202	254.73474	479	0.531805308
		306406.678	1535.85318	350.5421293	199.50258	532	0.375004857
	Average Sl/D 2	270623.9949	998.5200263	389.6495918	271.0251	420	0.645297869
		297471.2563	1825.120193	360.3841956	162.98721	475	0.343130978

Table 4.5: Comparing Performance Parameters of Varying vs Constant St/D per Zone for 4 Zones

To better visualize the difference between implementations, the results are plotted in figures 4.12 and 4.13 for scarcely and densely packed cases, respectively. The plots compare the Reynolds number, pressure drop, heat transfer, heat transfer coefficient (HTC), and temperature for each tube row section.

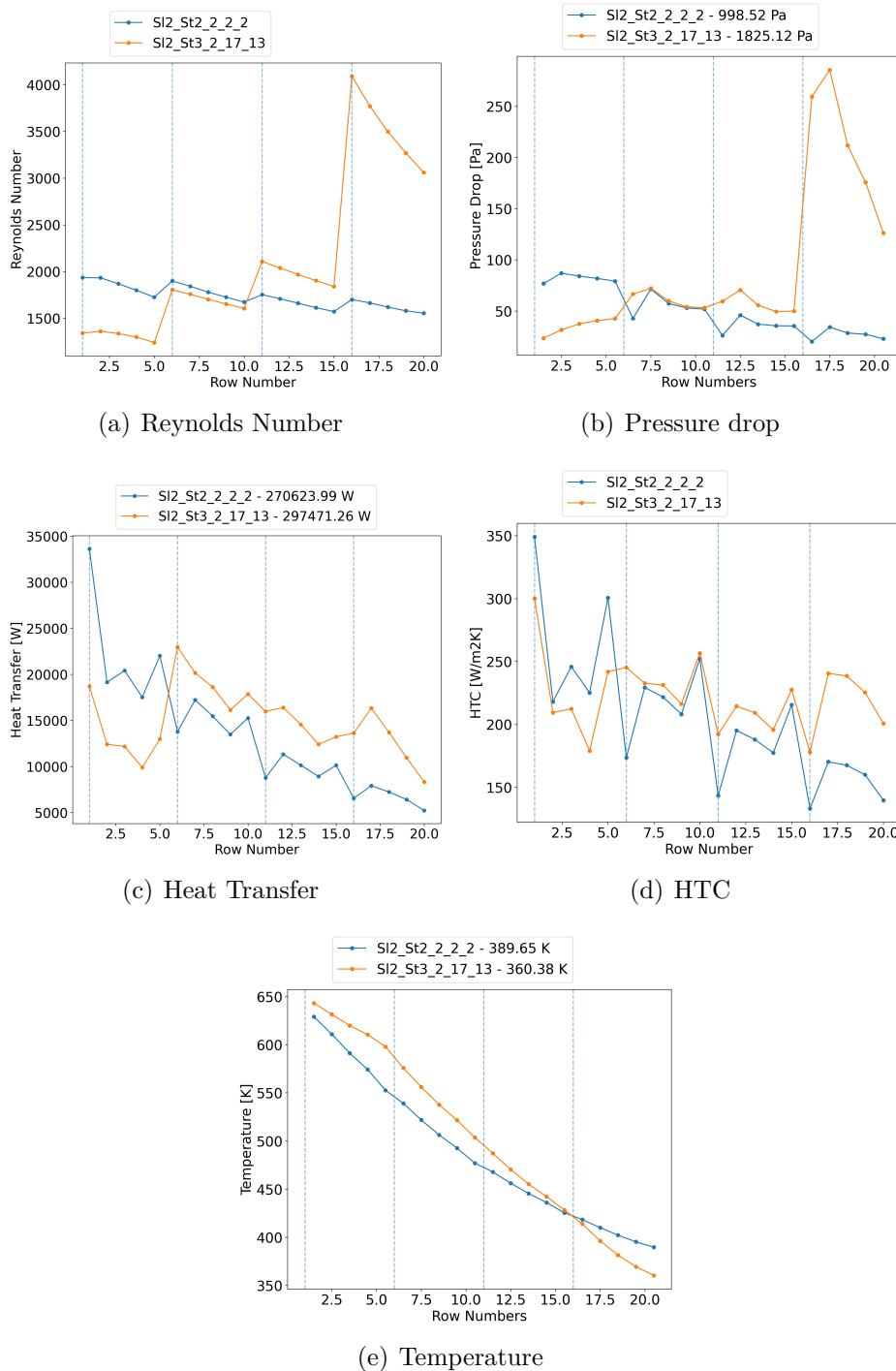


Figure 4.12: Constant vs Variable zoning for a scarcely packed case

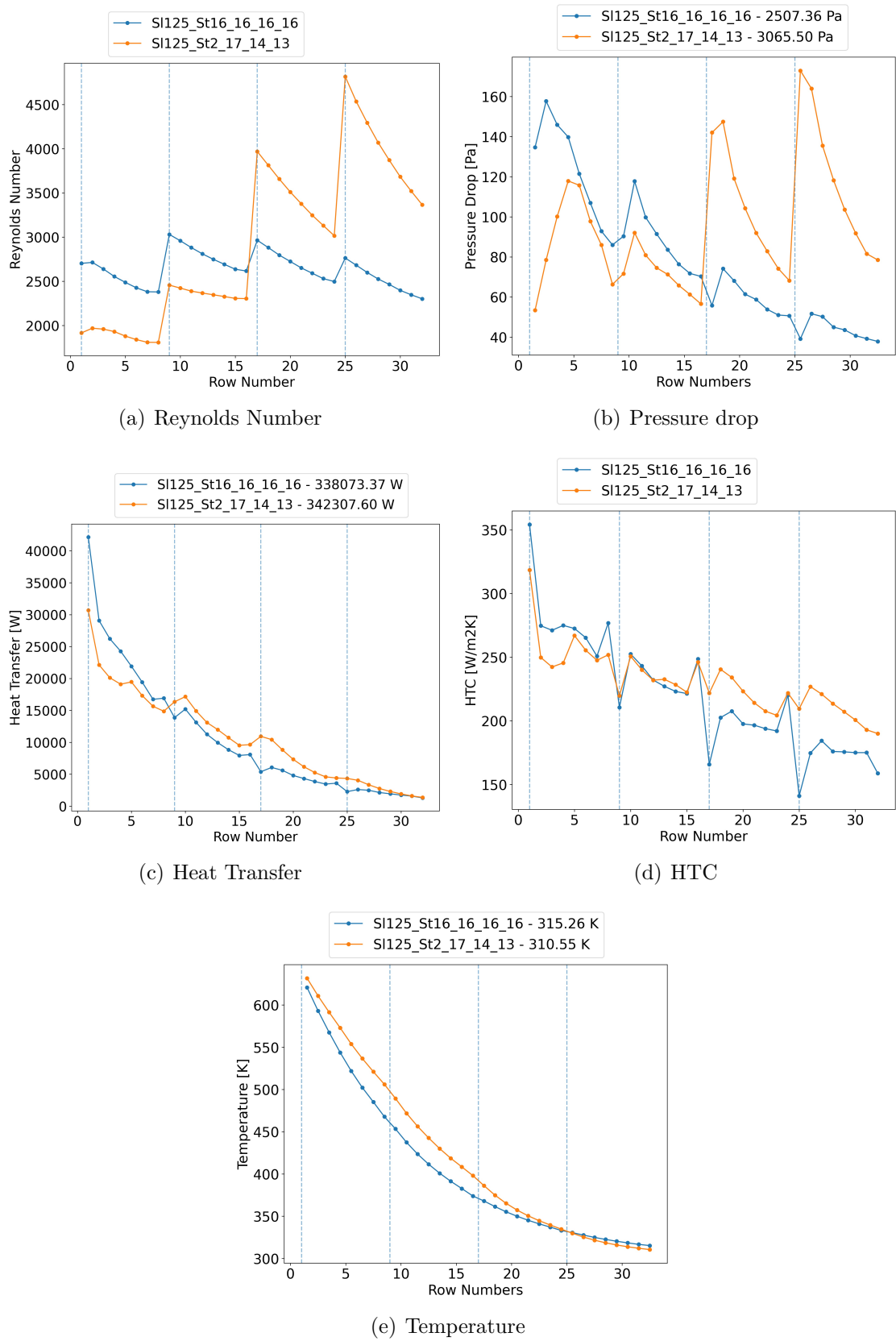


Figure 4.13: Constant vs Variable zoning for a densely packed case

Figures 4.12 and 4.13 show a gradual decrease in pressure losses and heat transfer for each row section in the constant zoning cases, attributed to the decreasing Reynolds number trend. This trend does not hold for variable zoning cases. Lower pitch ratios and tighter packing increase the Reynolds number, resulting in a general upward trend in pressure drop as shown in figures 4.13(b) and 4.12(b). The heat transfer and HTC values remain fairly constant in the scarce case and decline at a slower rate in the dense case, as illustrated in figures 4.13(c) and 4.13(d).

It can also be seen in tables 4.4 and 4.5 that the heat transfer-to-pressure drop ratio (HT/dP) is higher in cases with a constant St/D ratio, particularly in the scarce case. The higher HT/dP ratio in the constant zoning cases indicates that heat can be exchanged more efficiently for lesser pressure losses, making constant zoning preferable for a more efficient heat exchange if volume constraints are not significant. This is also evident when looking at performance per tube, where constant zoning cases outperform variable zoning cases, as the constant zone cases also have less number of tubes.

Performance comparison in terms of HT/dP and HT/dP per tube of all the constant and variable zoning cases for 4 zones are illustrated in the fig. 4.14 and fig. 4.15.

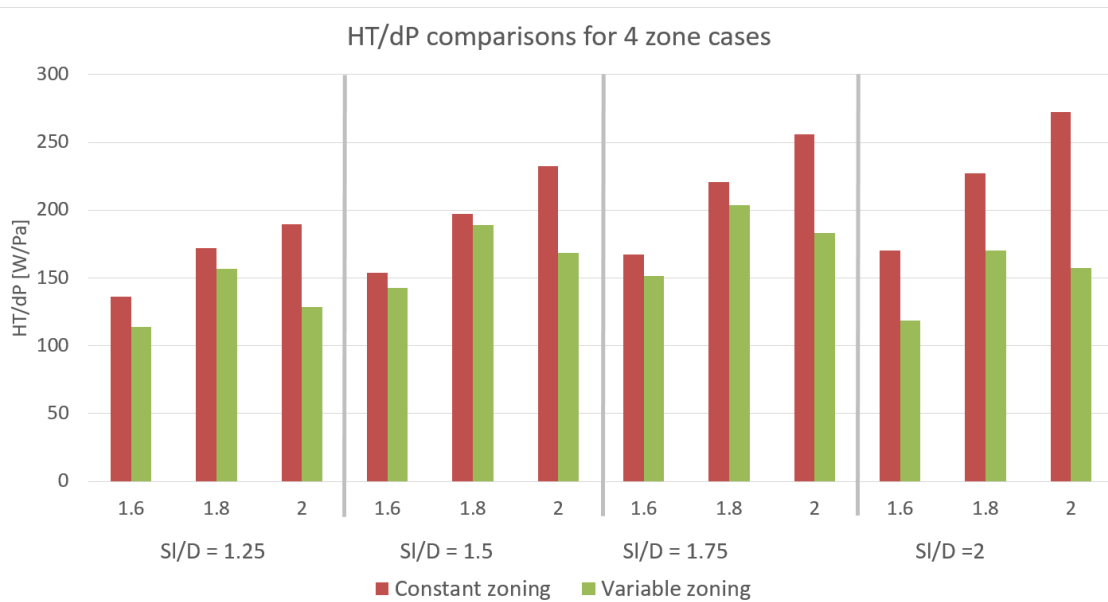


Figure 4.14: Comparing HT/dP performance for all constant and variable zoning cases for 4 zones

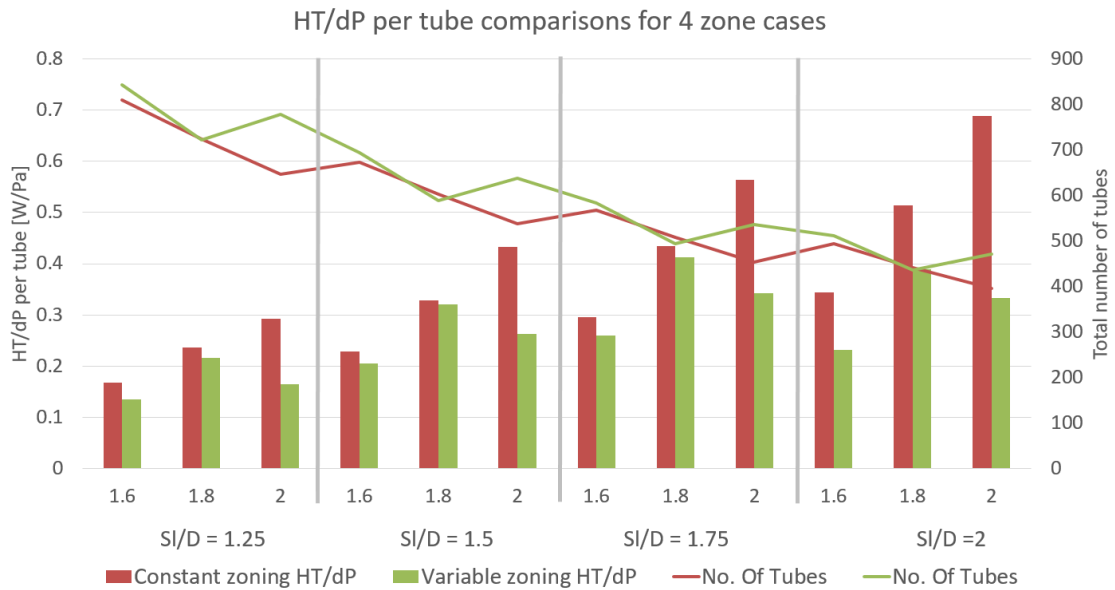


Figure 4.15: Comparing HT/dP per tube for all constant and variable zoning cases for 4 zones

Figure 4.14 summarises that all constant zoning cases outperform variable zoning cases when there are 4 zones. A similar trend was observed with 3 zones.

Figure 4.15 on the other hand shows that, in almost all instances, variable zoning cases consistently contain more tubes than constant zoning cases. Therefore, when comparing performance per tube, constant zoning cases significantly outperform variable zoning cases. Since the number of tubes correlates with the weight of the heat exchanger, this indicates that constant zoning cases provide higher performance for a lower weight of the heat exchanger compared to variable zoning cases.

To illustrate the difference in performance, fig. 4.16 presents a trimmed version of the same scarcely packed case from fig. 4.12. Thus, by trimming off the fourth zone, the heat exchanger now only includes the first three zones up to the 15th row. The change in values can be noted in table 4.6.

Cases	Performance Parameters	4 zones	Trimmed 3 zones
<i>Sl2_St2_2_2_2</i>	HT/dP [W/Pa]	271.02	274.15
	Total no. of tubes	420	295
	HT/dP per tube [W/Pa]	0.645	0.929
<i>Sl2_St3_2_17_13</i>	HT/dP [W/Pa]	162.93	305.98
	Total no. of tubes	475	285
	HT/dP per tube [W/Pa]	0.358	1.073

Table 4.6: Difference in performance for a scarcely packed case with 4 zones and trimmed off 4th zone

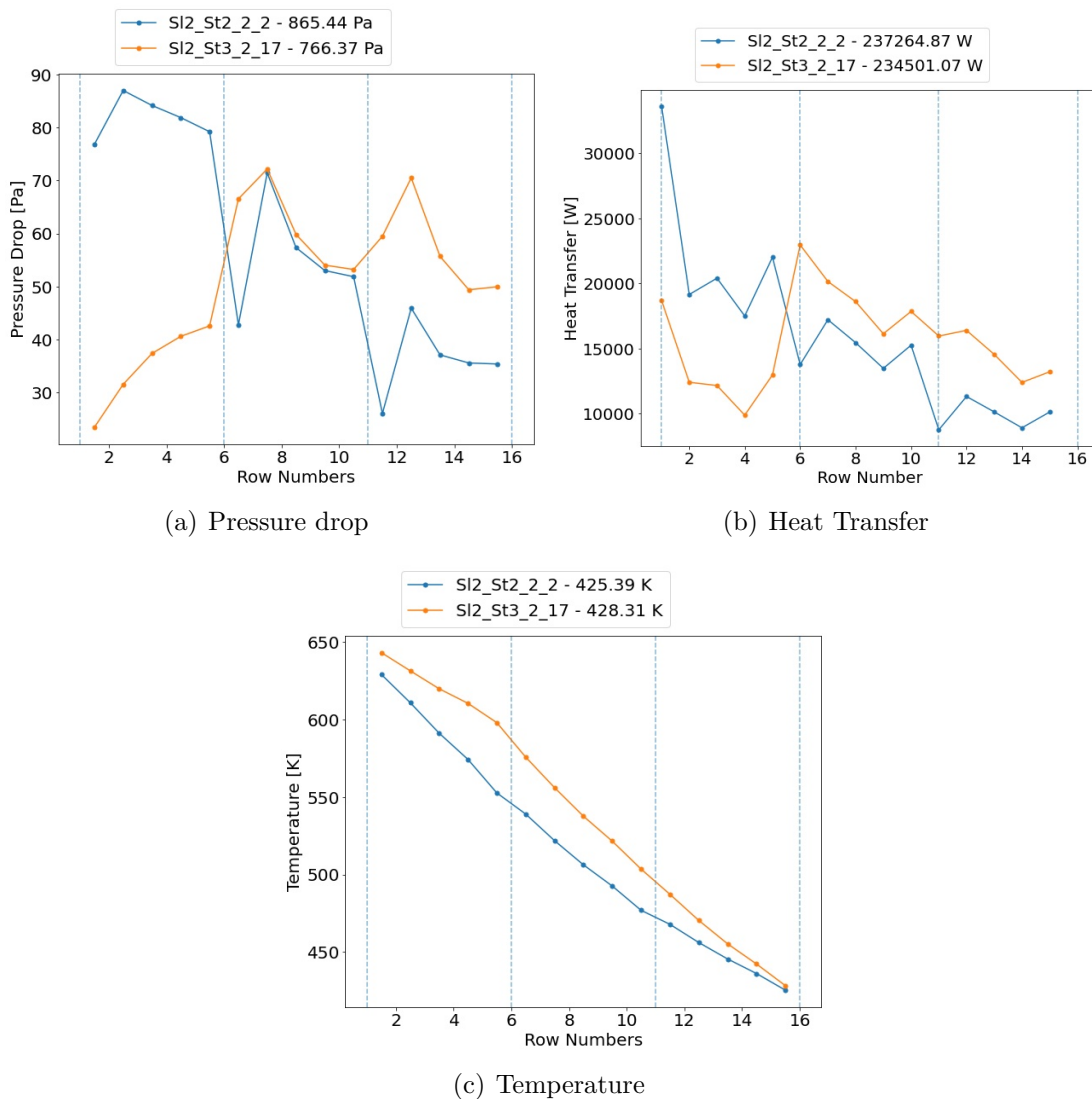


Figure 4.16: Scarcely packed case trimmed only upto 3 zones

It is interesting to observe that if the cooling demand is less such that the average outlet temperature could be 350K or 400K instead of 300K (wall temperature), the heat exchanger would then require less number of rows to meet that cooling demand indicating that the volume of the heat exchanger could be reduced. Lesser number

of tubes would also mean less weight of the heat exchanger resulting in higher tube performance. For instance, let us consider the scarcely packed cases with 4 zones (fig. 4.12(e)) where the fluid temperature nearly equalizes by the end of the 3rd zone, or 15th row. Trimming the heat exchanger to retain only 3 zones instead of 4 results in a notable shift in pressure losses and performance (refer table 4.6). Comparing both scenarios with all 4 zones intact reveals that constant zoning offers a higher HT/dP ratio. However, when considering the trimmed case with 3 zones, variable zoning outperforms constant zoning. Therefore, selecting the ideal configuration would depend on the specific requirements. Hence, if an outlet temperature of approximately 425K or a corresponding heat load of 235kW is needed, a variable zoning case [3,2,1.7] with 3 zones would be more sensible. Conversely, for other heat extraction needs, a different case might offer greater efficiency.

4.7 Effect of zones

To understand the effect of the number of zones on the performance of the heat exchanger, the results were plotted for different numbers of zones. Figures 4.17 and 4.18 show the general trends lines for scarcely and densely packed cases, respectively.

Convection dominates heat transfer in a heat exchanger, dependent on the temperature difference between the tubes and the fluid. As fluid temperature decreases outward, less heat is exchanged between the tubes and the fluid in the outer sections. For instance, Figure 4.18(d) shows a bulk temperature difference, ΔT , of approximately 50K for the first two rows, but only 3.5K for the last two rows, resulting in significantly reduced heat transfer in the latter rows. This occurrence is known as oversized heat exchangers. Thus if the heating or cooling loads are not very stringent, this phenomenon could be avoided due to its low heat transfer efficiency towards the outlet, particularly in densely packed configurations, as evident in figures 4.18(b) and 4.18(d).

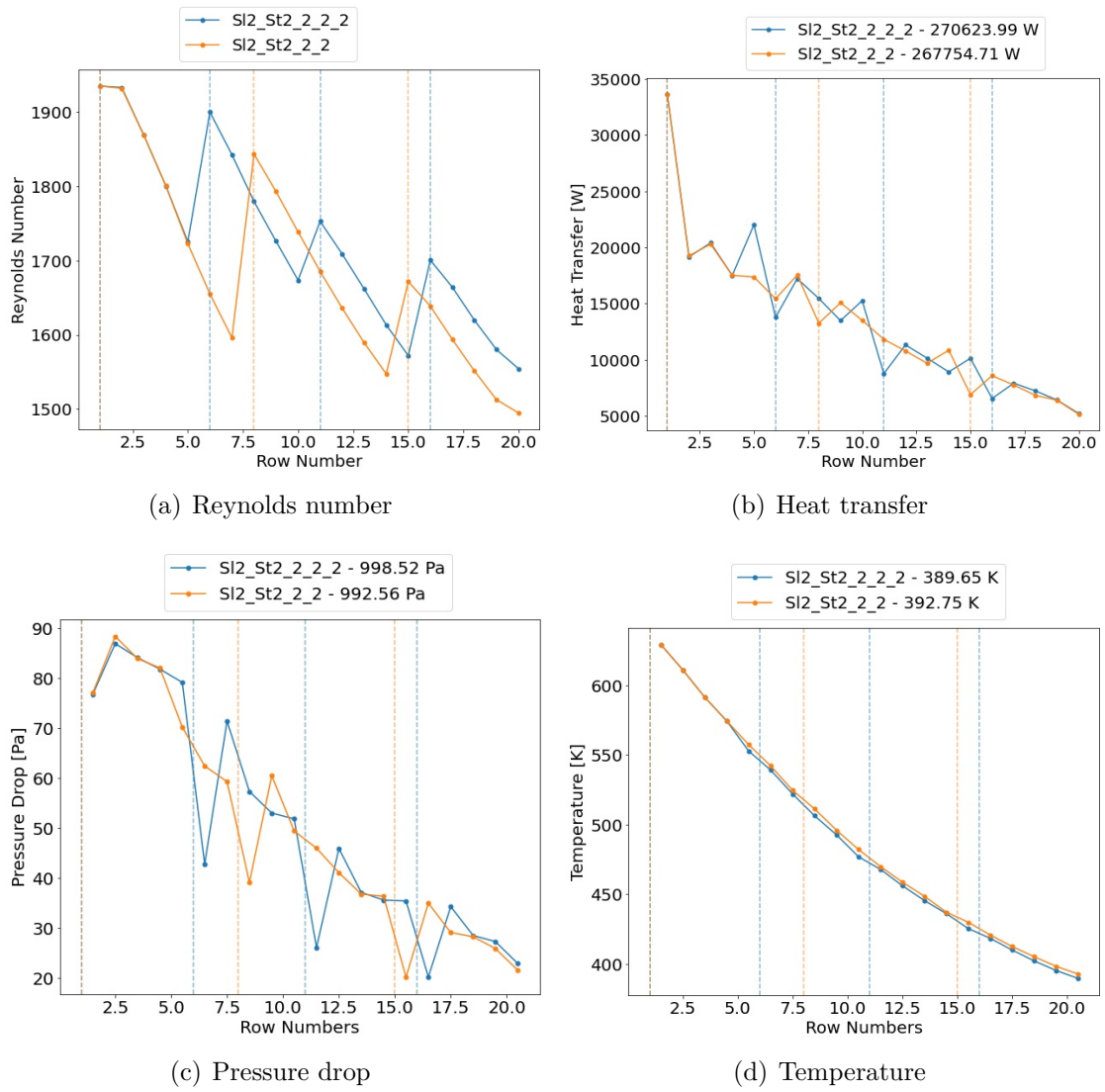


Figure 4.17: 4 zones vs 3 zones for a scarcely packed case $Sl/D = 2$ and $St/D=2$

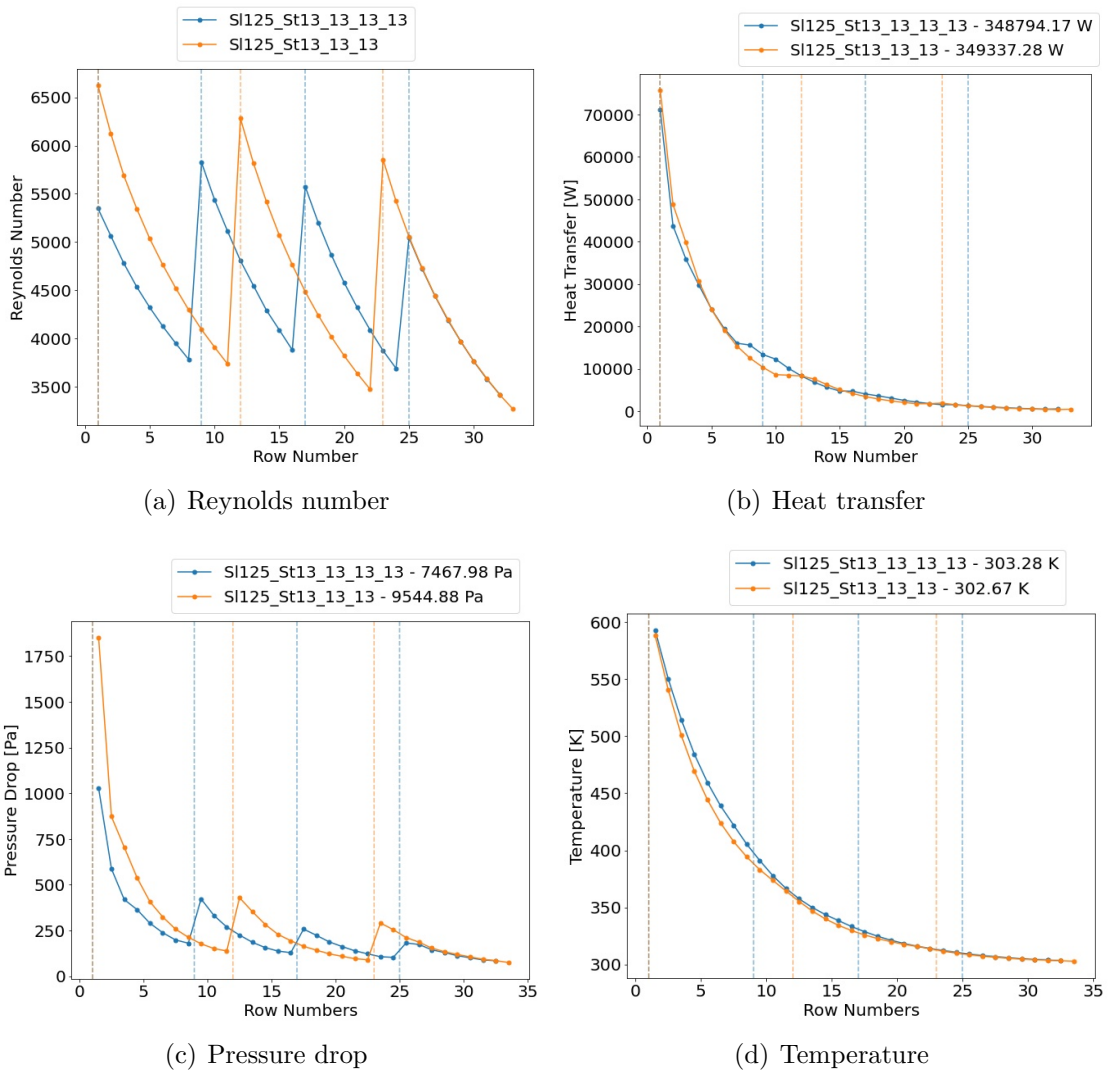


Figure 4.18: 4 zones vs 3 zones for a densely packed case $Sl/D = 1.25$ and $St/D=1.3$

In scarcely packed cases (fig. 4.17), performance remains consistent, with stable pressure drops, particularly in the initial section of the heat exchanger due to similar Reynolds numbers. However, densely packed configurations show higher Reynolds numbers and velocities in the first few rows, resulting in increased pressure losses (figure 4.18(c)). The overall rise in pressure drop leads to a lower HT/dP ratio.

Figure 4.19 illustrates the performance of the heat exchanger for different numbers of zones, ranging from 1 to 5 for a case with Sl/D ratio = 1.25 and average $St/D = 1.6$ for the whole annular section.

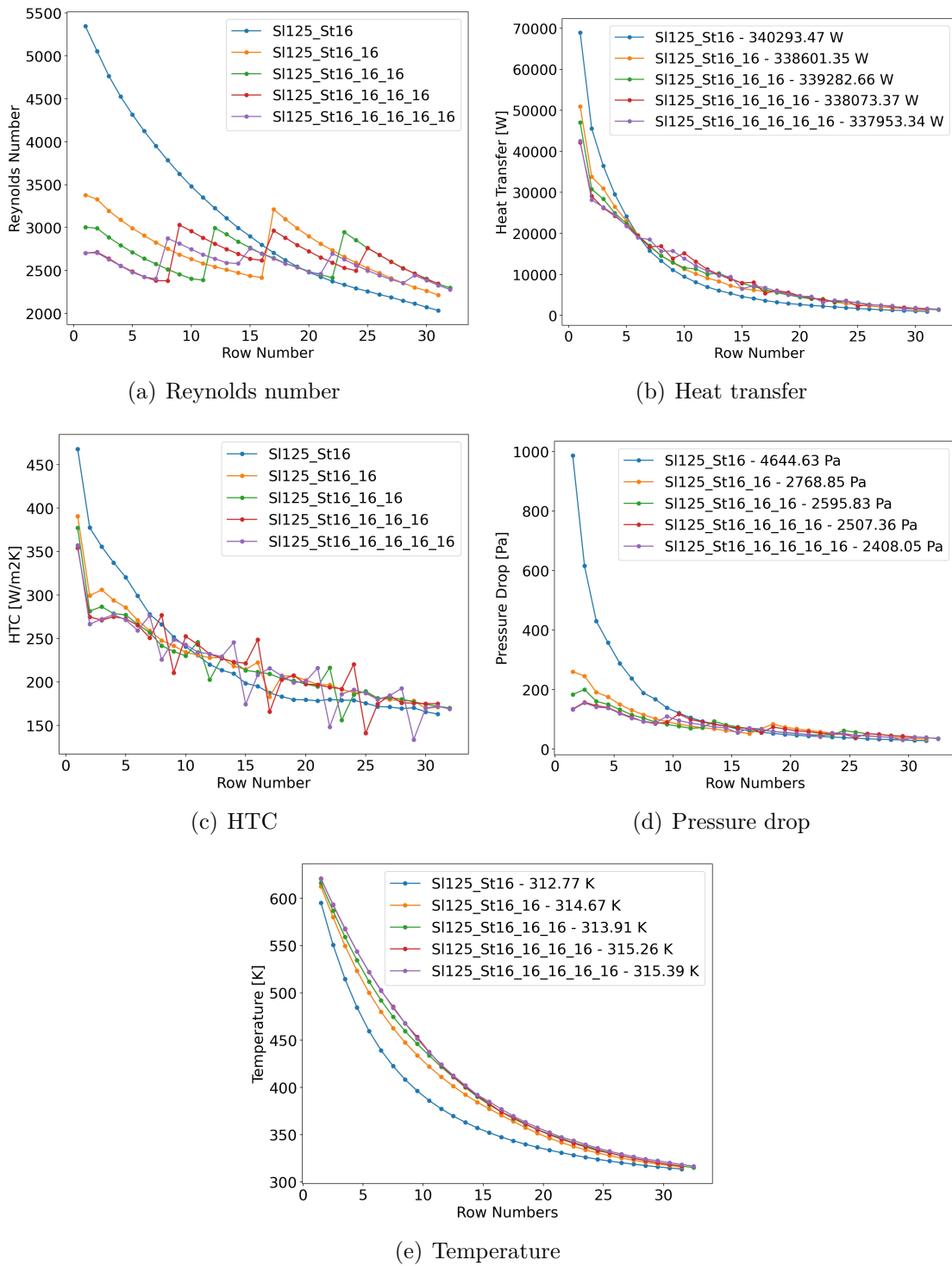


Figure 4.19: Performance plots varying from 1 to 5 zones for case SI125_St16_16_16_16

One might assume that increasing the number of zones could negatively impact heat transfer, given the sharp declines in HTC each time a zone is added (fig. 4.19(c)). However, this effect diminishes as one moves away from the inlet due to a decrease in temperature difference ΔT between two row sections. Consequently, even if heat extraction is limited in the initial rows, it tends to be compensated for in subsequent rows. This phenomenon is clearly illustrated in fig. 4.19(b), where a significant amount of heat is extracted from configurations featuring only one zone up to approximately row 5, after which the rate of heat transfer reduces. In contrast, cases with a higher number of zones exhibit a higher heat transfer rate than the first case after row 5. The higher temperature difference in later sections is balanced by the loss of potential heat transfer introduced when a new zone is added.

Figure 4.20 demonstrates that as the number of zones increases, there is a slight decrease in heat transfer, but a notable reduction in pressure losses across the entire section. The pressure drop can be noted particularly high in case featuring only one zone across the section due to exceedingly high Reynolds numbers in the initial rows(4.19(a)). Consequently, the performance of the heat exchanger shows a substantial improvement as the number of zones increases.

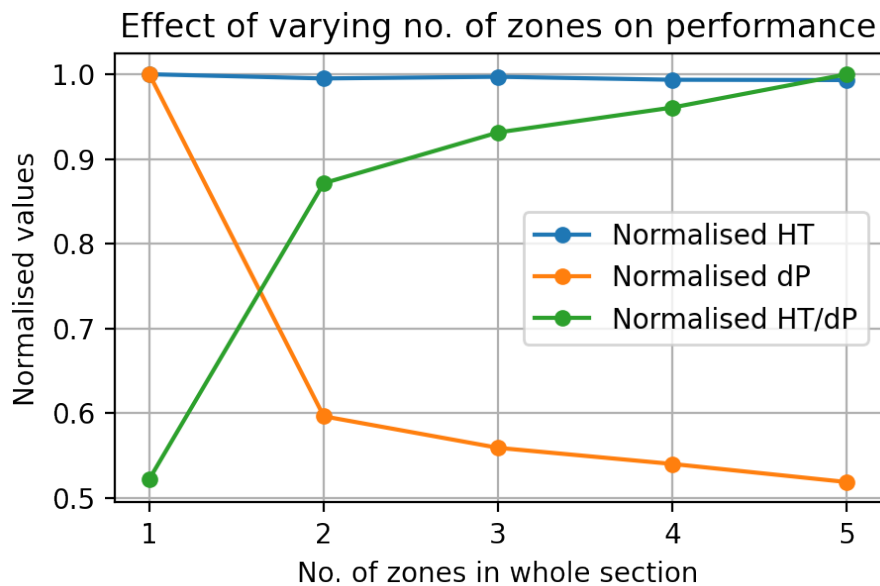


Figure 4.20: Effect of varying number of zones from 1 to 5 for a single case Sl15_St16_16_16_16

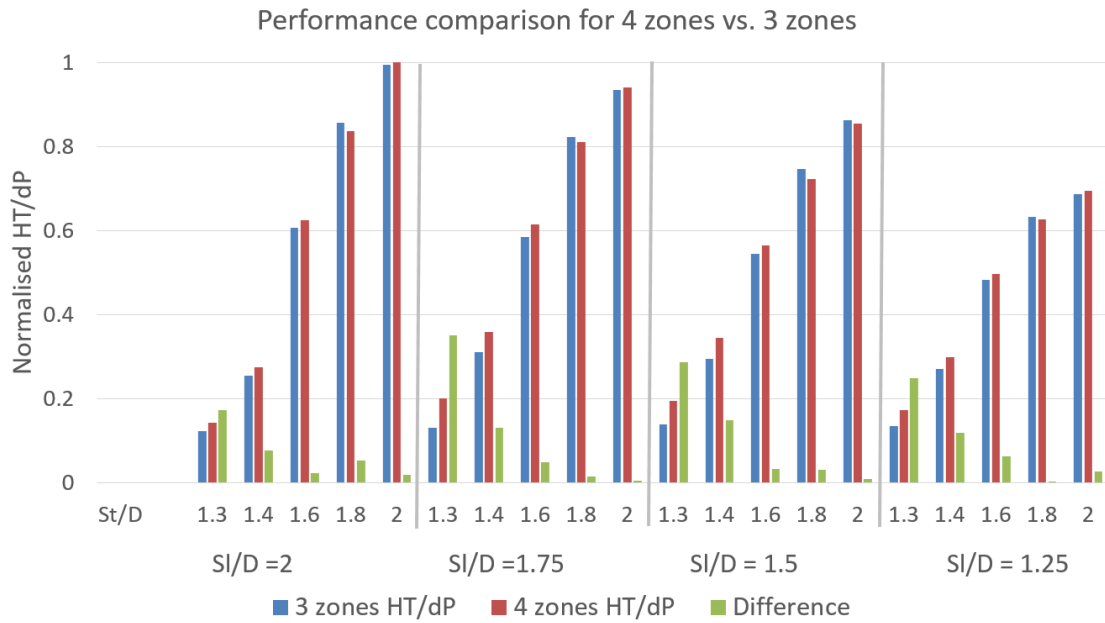


Figure 4.21: Performance of all cases - 4 zones vs 3 zones

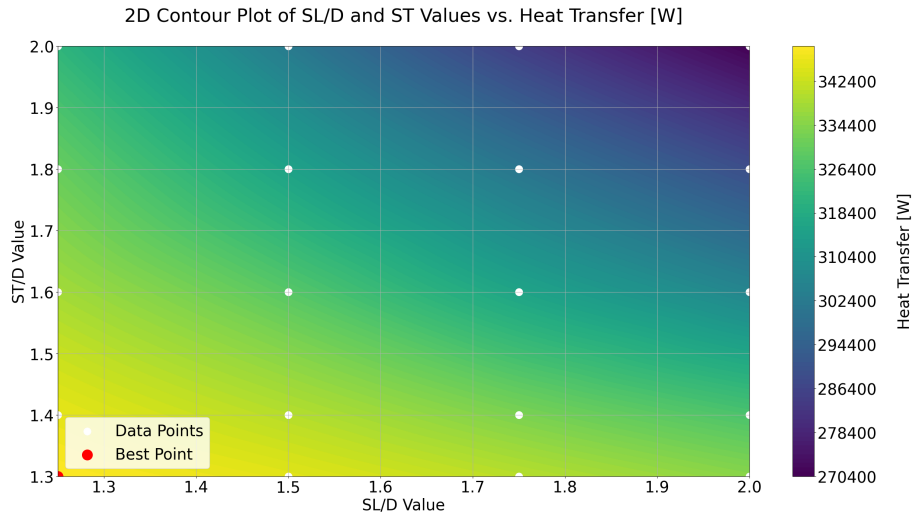
A histogram in figure 4.21 compiles the normalized HT/dP values plotted for all the cases with 3 and 4 zones. The green bars denote the percentage difference in normalized HT/dP values between corresponding cases. The plot summarises how nearly all cases with 4 zones outperform those with 3 zones. The largest differences in HT/dP values (green bars) were consistently observed for cases with $St/D=1.3$, regardless of the Sl/D ratio. Zoning significantly influences performance as St/D values decrease.

4.8 Overall Domain Performance:

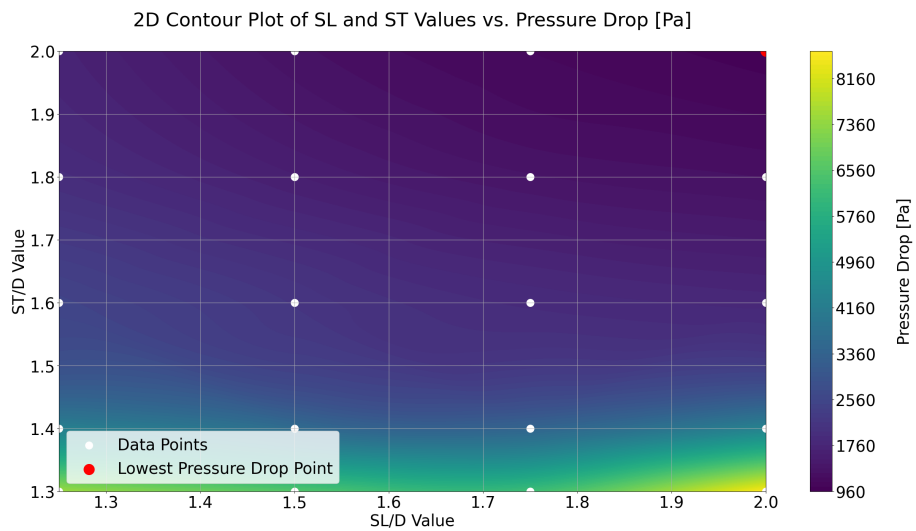
The overall performance of the domain was evaluated by plotting heatmaps of heat transfer, pressure drop, and the ratio of heat transfer to pressure drop. The results for 3 and 4 zones with constant and variable St/D are shown in the following sections.

4.8.1 Constant St/D with 4 zones

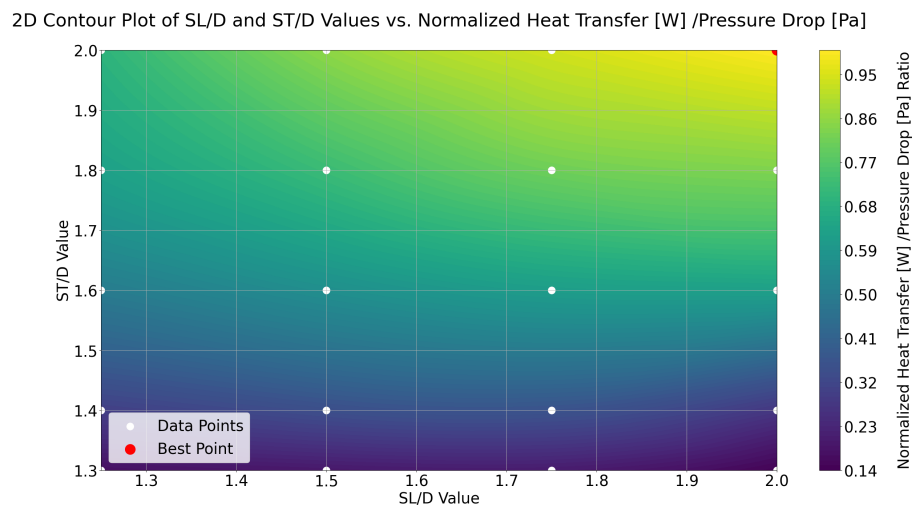
The heatmaps in fig. 4.22 show the performance of a domain of 4 zones with constant St/D for different parameters. The heat transfer, with a maximum HT at Sl/D of 1.3 and St/D of 1.25, and pressure drop, with minimum dP at Sl/D of 2 and St/D of 2, are plotted in figures 4.22(a) and 4.22(b) respectively. The normalized heat transfer to pressure drop ratio is shown in fig. 4.22(c) with a maximum Normalized HT/dP with Sl/D of 2 and St/D of 2.



(a) Heat transfer



(b) Pressure drop



(c) Normalized HT/dP

Figure 4.22: Heatmaps showing the performance of a domain of 4 zones with constant St/D for different parameters

4.8.2 Constant St/D with 3 zones

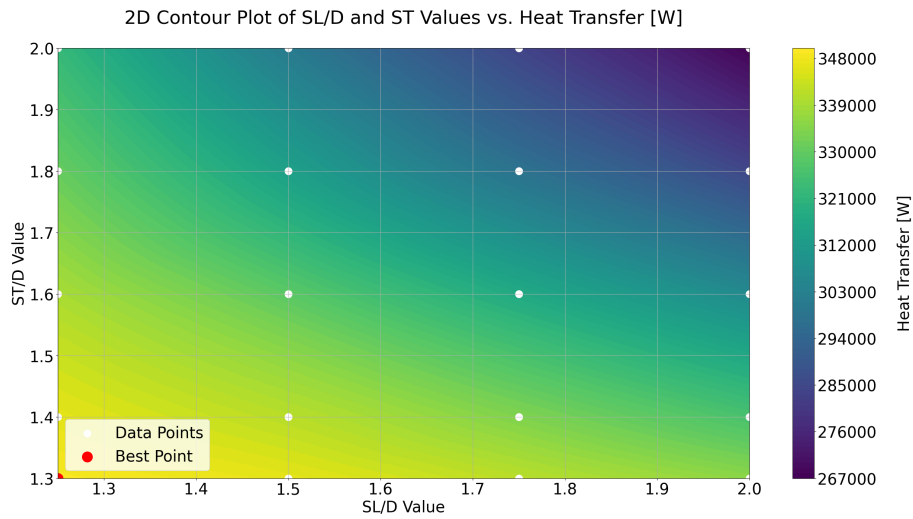
The heatmaps in fig. 4.23 show the performance of a domain of 3 zones with constant St/D for different parameters. The heat transfer, with a maximum HT at Sl/D of 1.3 and St/D of 1.25, and pressure drop, with minimum dP at Sl/D of 2 and St/D of 2, are plotted in figures 4.23(a) and 4.23(b) respectively. The normalized heat transfer to pressure drop ratio is shown in fig. 4.23(c) with a maximum Normalized HT/ dP with Sl/D of 2 and St/D of 2.

4.8.3 Variable St/D with 4 zones

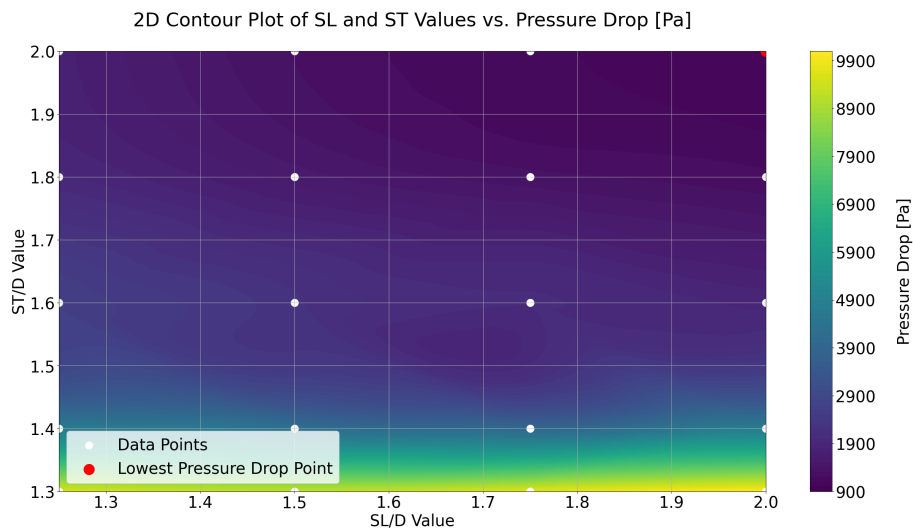
The heatmaps in fig. 4.24 show the performance of a domain of 4 zones with variable St/D for different parameters. The heat transfer, with a maximum HT at Sl/D of 1.25 and St/D of 1.6, and pressure drop, with a minimum dP at Sl/D of 1.75 and St/D of 2, are plotted in figures 4.24(a) and 4.24(b) respectively. The normalized heat transfer to pressure drop ratio is shown in fig. 4.24(c) with a maximum Normalized HT/ dp with Sl/D of 1.75 and St/D of 2.

4.8.4 Variable St/D with 3 zones

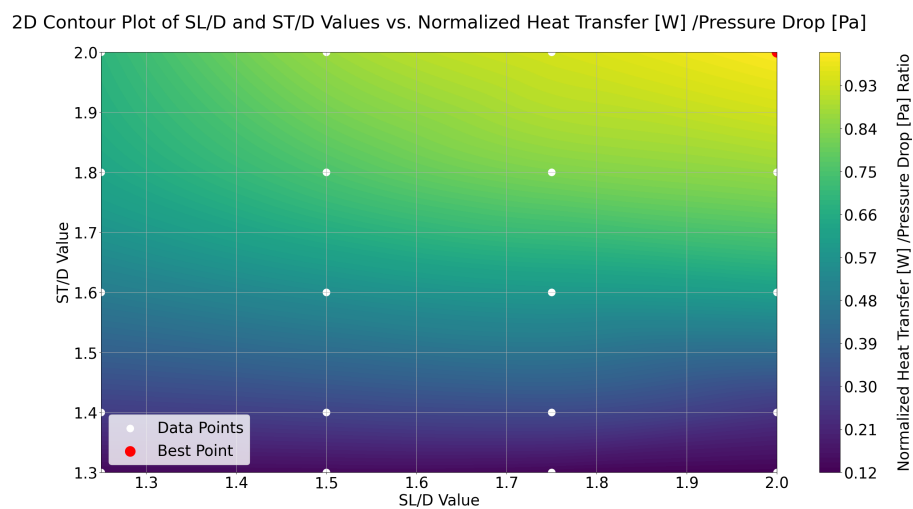
The heatmaps in fig. 4.25 show the performance of a domain of 3 zones with variable St/D for different parameters. The heat transfer, with a maximum HT at Sl/D of 1.25 and St/D of 1.6, and pressure drop, with a minimum dP at Sl/D of 1.75 and St/D of 2, are plotted in figures 4.25(a) and 4.25(b) respectively. The normalized heat transfer to pressure drop ratio is shown in fig. 4.25(c) with a maximum Normalized HT/ dp with Sl/D of 1.75 and St/D of 2.



(a) Heat transfer



(b) Pressure drop



(c) Normalized HT/dP

Figure 4.23: Heatmaps showing the performance of a domain of 3 zones with constant St/D for different parameters

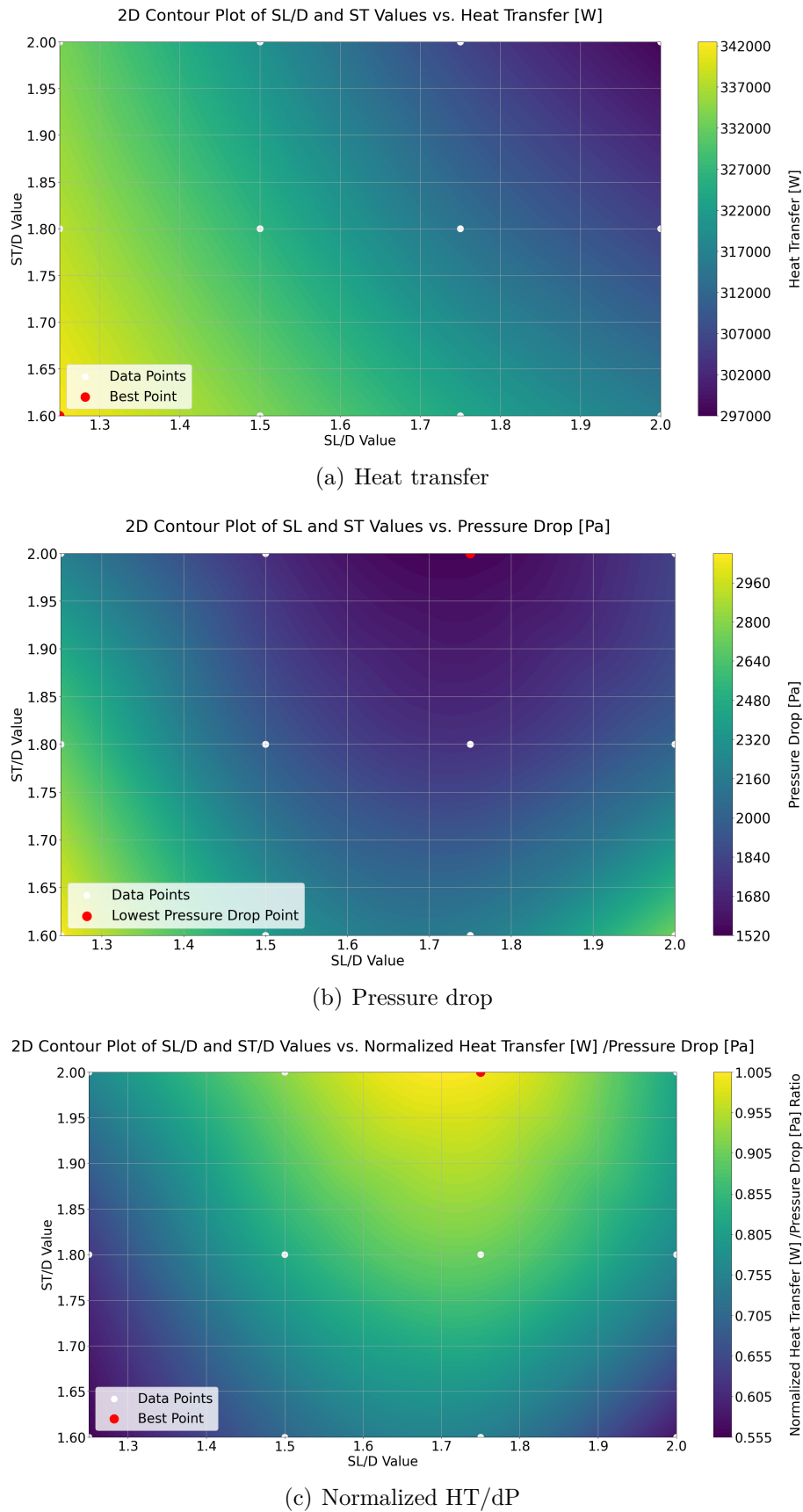


Figure 4.24: Heatmaps showing the performance of a domain of 4 zones with variable St/D for different parameters

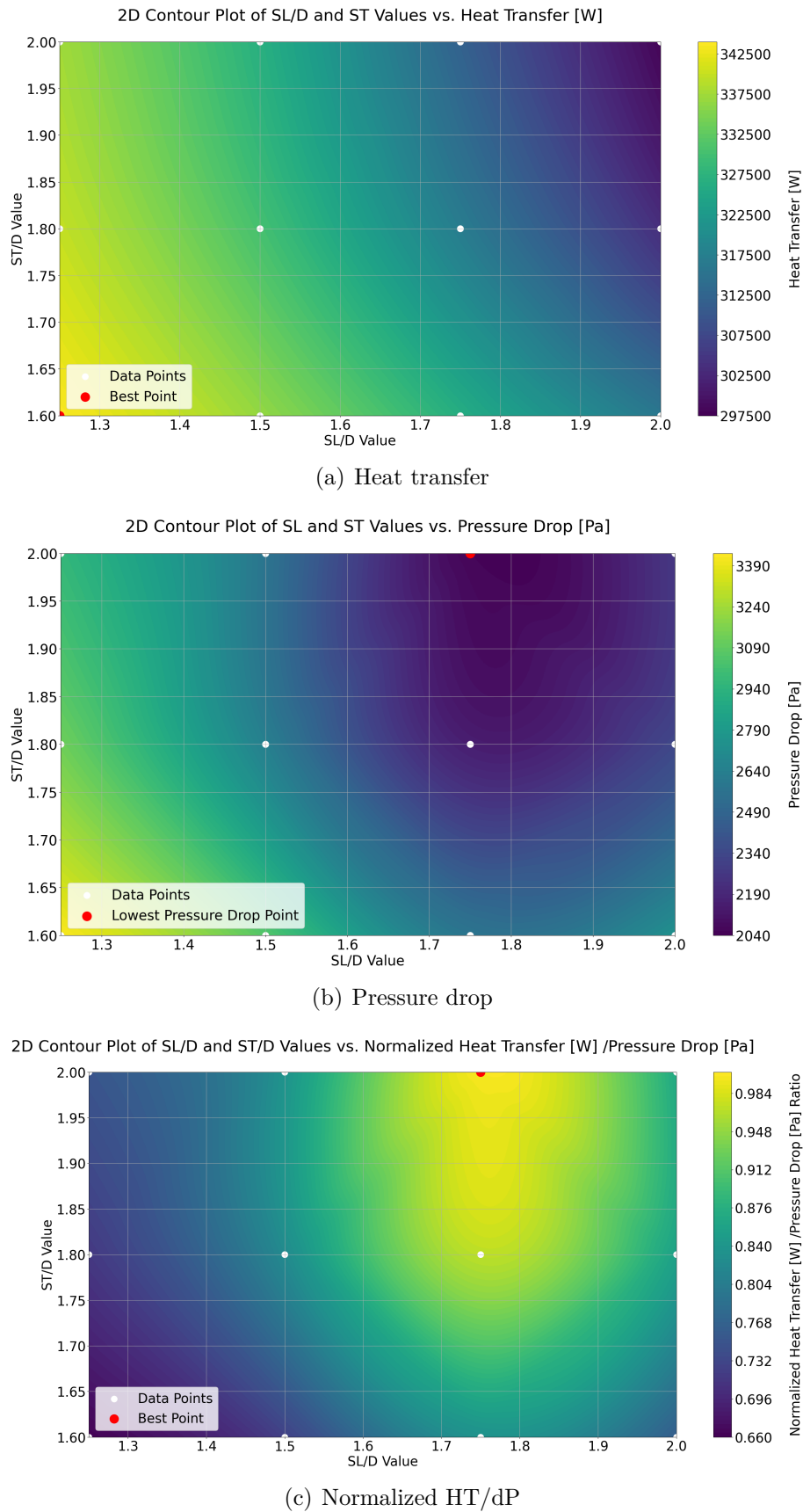


Figure 4.25: Heatmaps showing the performance of a domain of 3 zones with variable St/D for different parameters

4.8.5 Performance discrepancies between CFD and Correlations

The performance of the heat exchanger was compared to the correlations for heat transfer and pressure drop. The deviation of the CFD results from the correlations was plotted for different Sl/D and St/D values for 3 and 4 zones. The results are shown in the following sections.

4.8.5.1 4 Zones

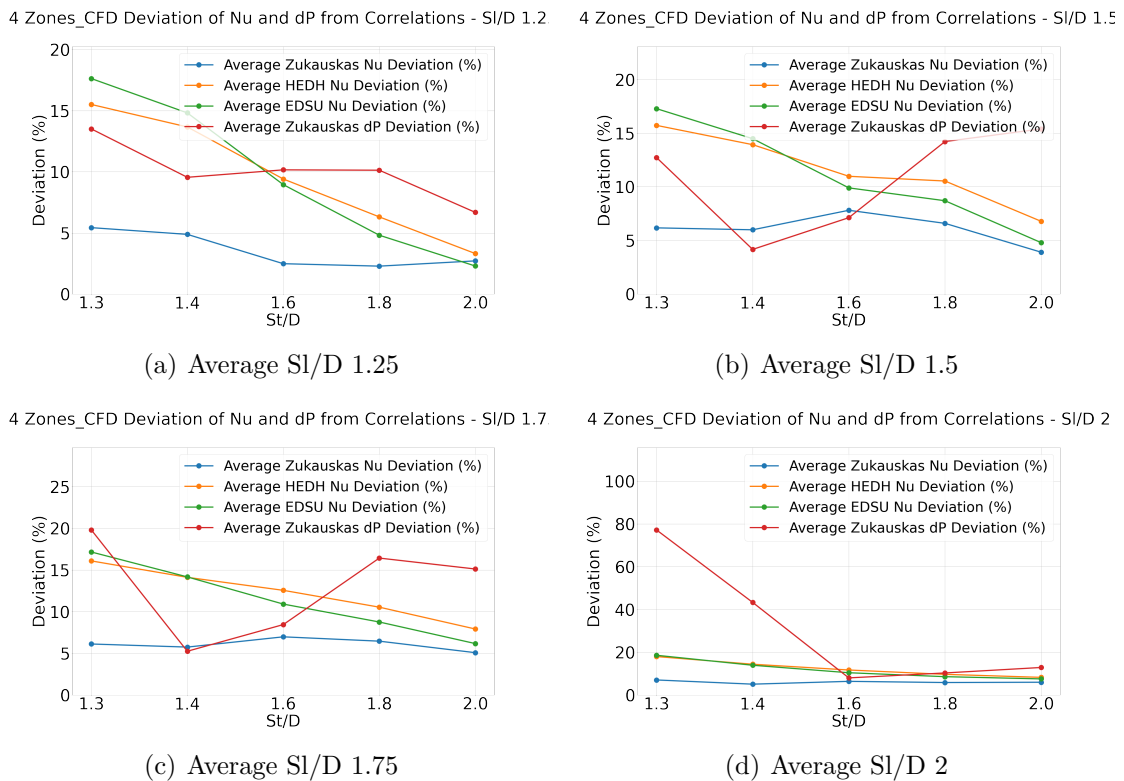


Figure 4.26: Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant Sl/D with 4 zones

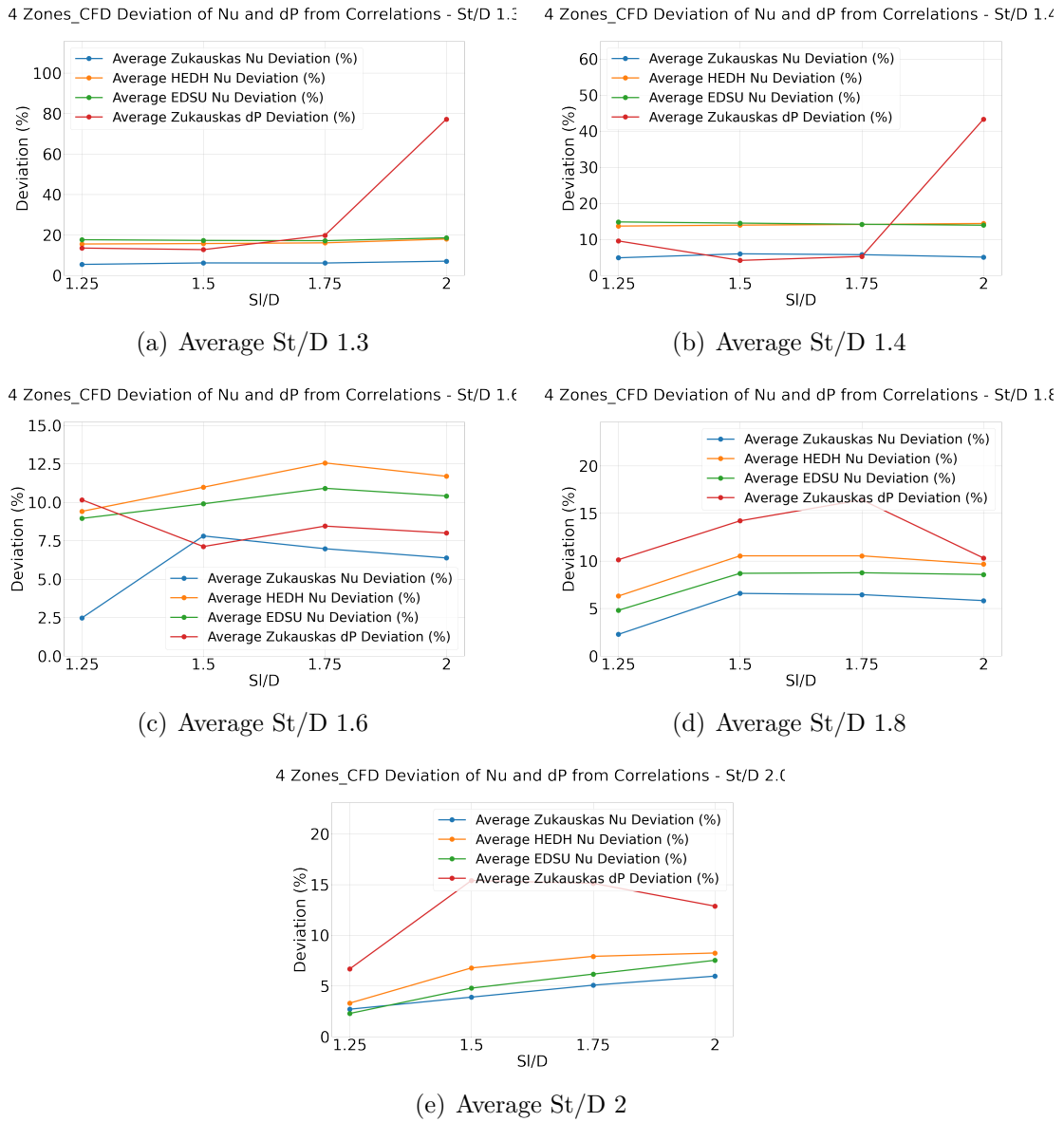


Figure 4.27: Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant St/D with 4 zones

4.8.5.2 3 Zones

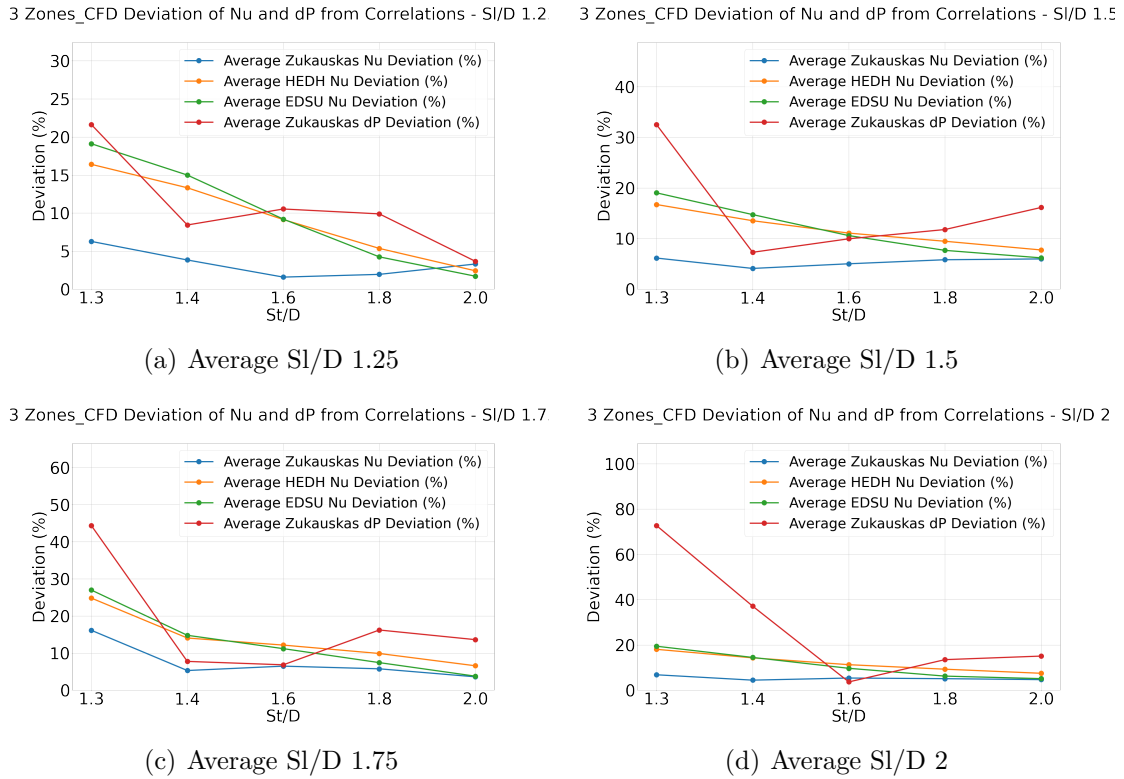


Figure 4.28: Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant Sl/D with 4 zones

The heat exchanger performance was compared with the Zukauskas correlation for pressure drop and Nusselt Number but also compared with HEDH and ESDU Nusselt number correlations. The deviations from correlations for the radial heat exchanger are not that far off from the correlation results of the rectangular case. The cause of increased deviation could be due to the fact that the correlations were not made for a radial heat exchanger with increasing spacing as one moves radially outwards, and instead made for a heat exchanger with constant spacing throughout the domain. The deviations are still low enough (sub 20% as maximum for Nusselt Number and pressure drop, with some outliers for pressure drop) to state that the results of the radial heat exchanger are in good agreement with the correlations.

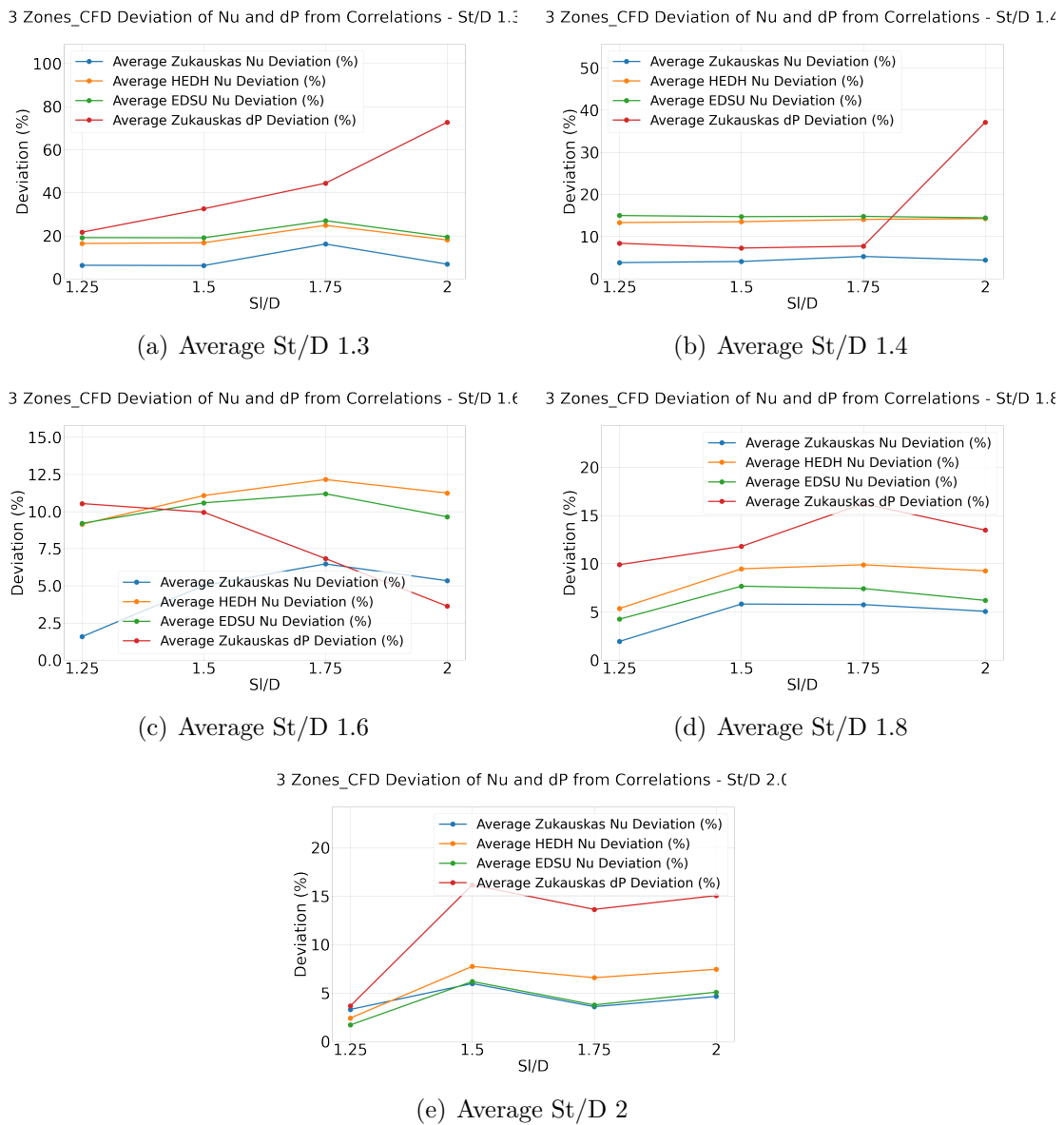


Figure 4.29: Plots showing the absolute deviation value of CFD Nu and dP values to Correlations for Constant St/D with 3 zones

The results show that for a constant Sl/D, the deviation from correlations has a, mostly, downwards trend with increasing St/D, this can be seen in figures 4.26 and 4.28. This could be due to the decrease in velocity as St/D decreases, since Nusselt Number and Pressure drop are both velocity dependent. However, for a constant St/D with increasing Sl/D, the error seems to increase as the spacing between rows increases, which can be seen in figures 4.27 and 4.29. As the spacing between tubes increases, the flow can become more unevenly distributed, or even show a form of inline flow with a staggered arrangement. this could lead to the formation of vortices, which are not necessarily taken into account with simpler correlation models, which can impact the heat transfer and pressure drop.

4.9 Misaligned flow

An interesting observation in some cases was the misaligned flow near the outlet, where instead of flowing radially outward, the flow tended to align in a specific direction, as illustrated in Fig. 4.4(a). No pattern was found out in such cases, and thus the cause of this is unclear. One guess could be that when a new zone is introduced, that transition zone between the two zones has tubes interfering with each other's flow. This transition could disrupt the flow and lead to misaligned flow. The misaligned flow could also be due to the meshing process, where the meshing algorithm might have had trouble with the complex geometry of the heat exchanger. The misaligned flow could have impacted the results, as the flow was not perpendicular to the tubes, which could have impacted the heat transfer and pressure drop. However, the misaligned flow did not seem to have a pattern, as it was not present in all cases with a high number of zones.

4.10 Use of SpaceClaim

SpaceClaim is a powerful tool for geometry generation and cleanup for simulations but is not optimal for 2-D modeling in this use case scenario. While geometry generation in SpaceClaim is fast, the meshing and file exporting process is time-consuming. For large workflow automation, time is crucial. One might assume 2-D geometry generation and meshing would be quick due to its simplicity compared to 3-D geometry, but this was not the case with SpaceClaim. However, SpaceClaim's built-in Python API allows for process automation. DesignModeler is recommended for faster, more efficient 2-D geometry generation and it can run on Linux. For meshing, tools like ANSA or ICEM CFD might prove more beneficial than SpaceClaim.

4.11 Future Work

With the code developed for this study, it is now quite simple to generate new cases and analyze them. The code can be easily modified to include new features, and several areas of interest can be explored further. Some of the potential areas of future work include:

1. **Effect of Number of Zones:** As discussed in section 4.7, the effect of zones on heat exchanger performance is quite significant. The trendline of normalized HT/dP shows an upward trend even at five zones in fig. 4.20. It would be intriguing to continue increasing the number of zones until perhaps each row has a constant St/D ratio. This approach might disrupt the staggered arrangement but would be interesting to observe the results and potentially gain new insights. Additionally, it would be valuable to compare the performance differences between variable zoning and constant zoning configurations.

2. **Cases with $Sl/D < 1.25$:** Due to the meshing limitations of SpaceClaim, cases with a longitudinal pitch ratio less than 1.25 were not explored. Since the maximum Reynolds number and maximum velocity remain unchanged until a critical Sl/D ratio is reached, it would be beneficial to investigate if tighter longitudinal packing could be advantageous.
3. **Staggered Arrangement:** When new tubes are added or a zone is introduced, some tubes get hidden by the previous row. A mathematical study could be conducted to quantify the loss or gain in staggeredness as tubes are added or removed from consecutive rows, and to analyze its effect on pressure drop and heat transfer.
4. **Effect of Reynolds Number:** It would be interesting to evaluate the performance of the same tube configurations in different flow regimes, such as laminar or fully turbulent flow. Currently, the study's Reynolds number range is between 2000-5000, which lies in the laminar-turbulent transition regime. Exploring different flow regimes could provide further insights into the heat exchanger's performance.
5. **3-D Geometry:** The study was limited to 2D geometry. However, 3D geometry could provide a more accurate representation of the heat exchanger's performance. It would be interesting to compare the results of 2D and 3D simulations to determine the accuracy of 2D simulations.

5

Conclusion

This report presents an in-depth study focused on the automation and evaluation process of radial flow heat exchangers. The primary aim is to analyze the impact of various tube arrangements on heat transfer, pressure drop, and overall performance using CFD.

The rectangular arrangement case study with constant transverse and longitudinal pitches showed that packing tubes longitudinally is more effective than transversely. In case of annular sections, higher HT/dP ratios can be achieved by increasing the number of zones in cases with constant zoning, where St/D is constant for each zone. Scarcely packed cases with high transverse and longitudinal pitches are preferable if volume and heat load constraints are not strict. The study also reveals that constant zoning generally outperforms variable zoning in terms of heat transfer per pressure drop, though variable zoning can outperform constant zoning depending on specific heat loads.

The discrepancy between CFD results and correlations was found to be minimal with the Zukauskas correlations in comparison with the others (HEDH, EDSU). The Nusselt number discrepancy between CFD results and the Zukauskas correlation was similar for the annular section with varying St/D as it was for the rectangular case with constant St/D , indicating the potential applicability of these correlations to variable pitch cases. However, pressure drop predictions showed poor agreement with the correlations overall.

The script developed for this thesis at GKN has significant capabilities for automating the entire CFD workflow. It allows for a large number of simulations to be conducted with minimal human intervention and input. The script offers full flexibility to the user, enabling the generation of a variety of geometric designs with different sector angles, tube diameters, longitudinal pitches, transverse pitches, constant or varying pitches, section lengths, and number of zones. The Python API in SpaceClaim facilitates the generation and automation of geometries and models through scripting, though another tool is recommended for meshing.

Bibliography

- [1] ANSYS (2006), *FLUENT Documentation*. ANSYS Inc.
- [2] Bardina, J.E., Huang, P.G., Coakley, T.J. (1997), *Turbulence Modeling Validation, Testing, and Development*, NASA Technical Memorandum, 110446. URL: <https://ntrs.nasa.gov/citations/19980017864>
- [3] Beale, S.B. and Spalding, D.B., *Numerical study of fluid flow and heat transfer in tube banks with stream-wise periodic boundary conditions*, Transactions of the CSME, 22, 4A, pp. 397-416, 1998.
- [4] Bird, R. B., Stewart, W. E., & Lightfoot, E. N. (2002). *Transport Phenomena*. John Wiley & Sons.
- [5] CFD Online. "Y Plus Wall Distance Estimation." URL: https://www.cfd-online.com/Wiki/Y_plus_wall_distance_estimation
- [6] Chien, K.-Y. (1982), *Predictions of Channel and Boundary-Layer Flows with a Low-Reynolds Number Turbulence Model*, AIAA Journal, Vol. 20, No. 1, pp. 33-38. DOI: 10.2514/3.51043
- [7] Henrik S., Sonny A., Anders L., Patent WO2024003083A1, Exhaust cone heat exchangers. URL: <https://patents.google.com/patent/WO2024003083A1/en>
- [8] Bell, C. (2024), ht: Heat Transfer component of Chemical Engineering Design Library (ChEDL). URL: https://ht.readthedocs.io/en/latest/ht.conv_tube_bank.html
- [9] Schlunder, E. U., & International Center for Heat and Mass Transfer. (1987). *Heat Exchanger Design Handbook*. Hemisphere Pub. Corp.
- [10] Hugo Petersen Verfahrenstechnischer Anlagenbau, *Sulphuric Acid Manufacture, Heat-Exchange Efficiency First*. URL: <https://www.hugopetersen.de/>
- [11] Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons.
- [12] Jones, W. P., and Launder, B. E. (1972), *The Prediction of Laminarization with a Two-Equation Model of Turbulence*, *International Journal of Heat and Mass Transfer*, vol. 15, pp. 301-314. DOI: 10.1016/0017-9310(72)90076-2
- [13] Kakac, S., Liu, H., & Pramuanjaroenkij, A. (2012). *Heat Exchangers: Selection, Rating, and Thermal Design*. CRC Press.
- [14] Kreith, F., & Manglik, R. M. (2018). *Principles of Heat Transfer*. Cengage Learning. ISBN 9781337516921. <https://www.vitalsource.com/products/principles-of-heat-transfer-frank-kreith-v9781337516921>
- [15] Launder, B. E. and Sharma, B. I. (1974), *Application of the Energy-Dissipation Model of Turbulence to the Calculation of Flow Near a Spinning Disc*, *Let-*

- ters in *Heat and Mass Transfer*, Vol. 1, No. 2, pp. 131-138. DOI: 10.1016/0094-4548(74)90150-7
- [16] Menter, F. R. (1993), *Zonal Two Equation $k - \omega$ Turbulence Models for Aerodynamic Flows*, *AIAA Paper*, 93-2906. DOI: 10.2514/6.1993-2906
- [17] Menter, F. R. (1994), *Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications*, *AIAA Journal*, vol. 32, no 8. pp. 1598-1605. DOI: 10.2514/3.12149
- [18] Menter, F., Esch, T. (2001), *Elements of industrial heat transfer predictions*, COBEM 2001, 16th Brazilian Congress of Mechanical Engineering. URL: https://www.researchgate.net/publication/243773217_Elements_of_industrial_heat_transfer_predictions
- [19] Nagano, Y. and Tagawa, M. (1990), *An Improved k -epsilon Model for Boundary Layer Flows*, *Journal of Fluids Engineering*, Vol. 112, pp. 33-39. DOI: 10.1115/1.2909418
- [20] Patel, V. C., Rodi, W., & Scheuerer, G. (1985), *Turbulence Models for Near-Wall and Low Reynolds Number Flows: A Review*, *AIAA Journal*, Vol. 23, No. 9, pp. 1308-1319. DOI: 10.2514/3.9046
- [21] Rodi, W. and Mansour, N. N. (1993), *Low Reynolds Number k -epsilon Modeling with the Aid of Direct Simulation Data*, *Journal of Fluid Mechanics*, Vol. 250, pp. 509-529. DOI: 10.1017/S0022112093001530
- [22] Sensorex (2024). *A Comprehensive Overview of Heat Exchangers*. Retrieved from <https://sensorex.com/articles/comprehensive-overview-of-heat-exchangers>
- [23] Shah, R. K., & Sekulic, D. P. (2003). *Fundamentals of Heat Exchanger Design*. John Wiley & Sons, Inc. ISBN: 978-0471321712. <https://onlinelibrary.wiley.com/doi/book/10.1002/9781118671627>
- [24] Thulukkanam, K. (2013). *Heat Exchanger Design Handbook*, Second Edition. CRC Press.
- [25] Verein Deutscher Ingenieure. (2010). *VDI Heat Atlas*. Springer-Verlag Berlin Heidelberg. DOI: 10.1007/978-3-540-77877-6
- [26] Wilcox, David C. (1998). *Turbulence Modeling for CFD*. Second edition. Anaheim: DCW Industries, 1998. pp. 174.
- [27] Zukauskas, A. (1972). Heat transfer from tubes in crossflow. In T.F. Irvine, Jr. & J. P. Hartnett (Eds.), *Advances in Heat Transfer*, Vol. 8 (pp. 93-160). Academic Press, Inc., New York. DOI: 10.1016/S0065-2717(08)70050-9

A

Appendix 1

A.1 Results for Sl125 St13 13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	7467.975 Pa
Overall Results	Total Heat Transfer	348.794 kW
Overall Results	Mean HTC (CFD)	257.997 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	40.942
Overall Results	Total Number of Tubes	1024.0
Overall Results	Total Heat Transfer (Pipe) Area	16.085 m ²
Overall Results	Average Nu Deviation (Zu)	5.43%
Overall Results	Average Nu Deviation (HEDH)	15.51%
Overall Results	Average Nu Deviation (EDSU)	17.63%
Overall Results	Average dP Deviation	13.51%
Overall Results	HT/dP Ratio	46.71
Zone Results	Nu CFD	42.233, 41.855, 40.284, 37.712
Zone Results	Nu Zukauskas	41.801, 44.854, 44.054, 39.894
Zone Results	Nu HEDH	48.254, 50.182, 48.996, 44.471
Zone Results	Nu EDSU	48.724, 51.979, 50.651, 45.584
Zone Results	Deviation Zu	1.03%, 6.68%, 8.56%, 5.47%
Zone Results	Deviation HEDH	12.48%, 16.59%, 17.78%, 15.20%
Zone Results	Deviation EDSU	13.32%, 19.48%, 20.47%, 17.27%
Zone Results	Pressure Drop (Zukauskas)	3267.638 Pa, 1697.710 Pa, 1160.006 Pa, 767.852 Pa
Zone Results	Pressure Drop	3303.927 Pa, 1853.573 Pa, 1298.338 Pa, 1012.137 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	1.11%, 9.18%, 11.93%, 31.81%

Table A.1: Results for Sl125 St13 13 13 13 case

A.2 Results for Sl125 St13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	9544.879 Pa
Overall Results	Total Heat Transfer	349.337 kW
Overall Results	Mean HTC (CFD)	257.410 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	41.403
Overall Results	Total Number of Tubes	1067.0
Overall Results	Total Heat Transfer (Pipe) Area	16.760 m ²
Overall Results	Average Nu Deviation (Zu)	6.27%
Overall Results	Average Nu Deviation (HEDH)	16.40%
Overall Results	Average Nu Deviation (EDSU)	19.11%
Overall Results	Average dP Deviation	21.63%
Overall Results	HT/dP Ratio	36.60
Zone Results	Nu CFD	43.535, 40.803, 38.440
Zone Results	Nu Zukauskas	44.815, 44.708, 41.427
Zone Results	Nu HEDH	50.976, 49.644, 46.189
Zone Results	Nu EDSU	52.869, 51.377, 47.508
Zone Results	Deviation Zu	2.86%, 8.73%, 7.21%
Zone Results	Deviation HEDH	14.60%, 17.81%, 16.78%
Zone Results	Deviation EDSU	17.66%, 20.58%, 19.09%
Zone Results	Pressure Drop (Zukauskas)	4868.415 Pa, 1920.949 Pa, 1268.508 Pa
Zone Results	Pressure Drop	5634.924 Pa, 2206.617 Pa, 1703.338 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	15.74%, 14.87%, 34.28%

Table A.2: Results for Sl125 St13 13 13 case

A.3 Results for Sl125 St14 14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	4270.570 Pa
Overall Results	Total Heat Transfer	345.774 kW
Overall Results	Mean HTC (CFD)	238.030 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	36.593
Overall Results	Total Number of Tubes	960.0
Overall Results	Total Heat Transfer (Pipe) Area	15.080 m ²
Overall Results	Average Nu Deviation (Zu)	4.88%
Overall Results	Average Nu Deviation (HEDH)	13.67%
Overall Results	Average Nu Deviation (EDSU)	14.82%
Overall Results	Average dP Deviation	9.55%
Overall Results	HT/dP Ratio	80.97
Zone Results	Nu CFD	36.998, 37.112, 36.490, 34.562
Zone Results	Nu Zukauskas	36.163, 39.133, 39.269, 36.369
Zone Results	Nu HEDH	41.282, 43.358, 43.305, 40.257
Zone Results	Nu EDSU	41.089, 44.344, 44.282, 40.865
Zone Results	Deviation Zu	2.31%, 5.16%, 7.08%, 4.97%
Zone Results	Deviation HEDH	10.38%, 14.41%, 15.74%, 14.15%
Zone Results	Deviation EDSU	9.96%, 16.31%, 17.60%, 15.42%
Zone Results	Pressure Drop (Zukauskas)	2012.834 Pa, 1127.859 Pa, 781.255 Pa, 526.194 Pa
Zone Results	Pressure Drop	1748.813 Pa, 1093.738 Pa, 794.982 Pa, 633.036 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	13.12%, 3.03%, 1.76%, 20.30%

Table A.3: Results for Sl125 St14 14 14 14 case

A.4 Results for Sl125 St14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	4704.728 Pa
Overall Results	Total Heat Transfer	346.412 kW
Overall Results	Mean HTC (CFD)	236.591 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	36.880
Overall Results	Total Number of Tubes	990.0
Overall Results	Total Heat Transfer (Pipe) Area	15.551 m ²
Overall Results	Average Nu Deviation (Zu)	3.83%
Overall Results	Average Nu Deviation (HEDH)	13.32%
Overall Results	Average Nu Deviation (EDSU)	14.99%
Overall Results	Average dP Deviation	8.43%
Overall Results	HT/dP Ratio	73.63
Zone Results	Nu CFD	38.225, 36.967, 34.251
Zone Results	Nu Zukauskas	38.301, 39.444, 36.054
Zone Results	Nu HEDH	43.091, 43.404, 39.758
Zone Results	Nu EDSU	44.044, 44.395, 40.307
Zone Results	Deviation Zu	0.20%, 6.28%, 5.00%
Zone Results	Deviation HEDH	11.29%, 14.83%, 13.85%
Zone Results	Deviation EDSU	13.21%, 16.73%, 15.02%
Zone Results	Pressure Drop (Zukauskas)	2803.342 Pa, 1236.817 Pa, 704.941 Pa
Zone Results	Pressure Drop	2619.190 Pa, 1264.064 Pa, 821.474 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	6.57%, 2.20%, 16.53%

Table A.4: Results for Sl125 St14 14 14 case

A.5 Results for Sl125 St16 16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	2408.054 Pa
Overall Results	Total Heat Transfer	337.953 kW
Overall Results	Mean HTC (CFD)	215.762 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.815
Overall Results	Total Number of Tubes	855.0
Overall Results	Total Heat Transfer (Pipe) Area	13.430 m ²
Overall Results	Average Nu Deviation (Zu)	10.01%
Overall Results	Average Nu Deviation (HEDH)	9.61%
Overall Results	Average Nu Deviation (EDSU)	8.69%
Overall Results	Average dP Deviation	9.50%
Overall Results	HT/dP Ratio	140.34
Zone Results	Nu CFD	31.905, 32.847, 32.284, 31.231, 28.451
Zone Results	Nu Zukauskas	33.926, 36.235, 36.100, 35.492, 32.392
Zone Results	Nu HEDH	34.992, 36.146, 35.401, 34.871, 31.909
Zone Results	Nu EDSU	33.727, 36.226, 35.394, 34.801, 31.494
Zone Results	Deviation Zu	5.96%, 9.35%, 10.57%, 12.01%, 12.17%
Zone Results	Deviation HEDH	8.82%, 9.13%, 8.81%, 10.44%, 10.84%
Zone Results	Deviation EDSU	5.40%, 9.33%, 8.79%, 10.26%, 9.66%
Zone Results	Pressure Drop (Zukauskas)	1105.743 Pa, 670.258 Pa, 416.877 Pa, 316.339 Pa, 212.063 Pa
Zone Results	Pressure Drop	885.233 Pa, 610.149 Pa, 411.184 Pa, 322.106 Pa, 179.382 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	19.94%, 8.97%, 1.37%, 1.82%, 15.41%

Table A.5: Results for Sl125 St16 16 16 16 case

A.6 Results for Sl125 St16 16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	2507.364 Pa
Overall Results	Total Heat Transfer	338.073 kW
Overall Results	Mean HTC (CFD)	219.875 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	32.317
Overall Results	Total Number of Tubes	840.0
Overall Results	Total Heat Transfer (Pipe) Area	13.195 m ²
Overall Results	Average Nu Deviation (Zu)	2.48%
Overall Results	Average Nu Deviation (HEDH)	9.41%
Overall Results	Average Nu Deviation (EDSU)	8.95%
Overall Results	Average dP Deviation	10.16%
Overall Results	HT/dP Ratio	134.83
Zone Results	Nu CFD	32.076, 33.358, 32.555, 30.287
Zone Results	Nu Zukauskas	31.049, 33.750, 33.510, 31.088
Zone Results	Nu HEDH	34.795, 36.825, 36.272, 33.710
Zone Results	Nu EDSU	33.988, 37.027, 36.407, 33.541
Zone Results	Deviation Zu	3.31%, 1.16%, 2.85%, 2.58%
Zone Results	Deviation HEDH	7.81%, 9.42%, 10.25%, 10.16%
Zone Results	Deviation EDSU	5.62%, 9.91%, 10.58%, 9.70%
Zone Results	Pressure Drop (Zukauskas)	1197.764 Pa, 746.431 Pa, 470.101 Pa, 298.932 Pa
Zone Results	Pressure Drop	985.366 Pa, 701.262 Pa, 473.527 Pa, 347.209 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	17.73%, 6.05%, 0.73%, 16.15%

Table A.6: Results for Sl125 St16 16 16 16 case

A.7 Results for Sl125 St16 16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	2595.830 Pa
Overall Results	Total Heat Transfer	339.283 kW
Overall Results	Mean HTC (CFD)	218.155 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	32.391
Overall Results	Total Number of Tubes	869.0
Overall Results	Total Heat Transfer (Pipe) Area	13.650 m ²
Overall Results	Average Nu Deviation (Zu)	1.58%
Overall Results	Average Nu Deviation (HEDH)	9.14%
Overall Results	Average Nu Deviation (EDSU)	9.20%
Overall Results	Average dP Deviation	10.53%
Overall Results	HT/dP Ratio	130.70
Zone Results	Nu CFD	32.700, 32.759, 30.955
Zone Results	Nu Zukauskas	32.410, 33.306, 31.656
Zone Results	Nu HEDH	35.836, 35.926, 34.336
Zone Results	Nu EDSU	35.919, 36.021, 34.240
Zone Results	Deviation Zu	0.89%, 1.64%, 2.22%
Zone Results	Deviation HEDH	8.75%, 8.82%, 9.85%
Zone Results	Deviation EDSU	8.96%, 9.06%, 9.59%
Zone Results	Pressure Drop (Zukauskas)	1614.121 Pa, 737.661 Pa, 445.923 Pa
Zone Results	Pressure Drop	1368.997 Pa, 719.005 Pa, 507.828 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	15.19%, 2.53%, 13.88%

Table A.7: Results for Sl125 St16 16 16 16 case

A.8 Results for Sl125 St16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	2768.846 Pa
Overall Results	Total Heat Transfer	338.601 kW
Overall Results	Mean HTC (CFD)	222.851 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	33.272
Overall Results	Total Number of Tubes	832.0
Overall Results	Total Heat Transfer (Pipe) Area	13.069 m ²
Overall Results	Average Nu Deviation (Zu)	9.29%
Overall Results	Average Nu Deviation (HEDH)	8.16%
Overall Results	Average Nu Deviation (EDSU)	8.28%
Overall Results	Average dP Deviation	10.63%
Overall Results	HT/dP Ratio	122.29
Zone Results	Nu CFD	33.991, 31.989
Zone Results	Nu Zukauskas	37.161, 35.566
Zone Results	Nu HEDH	36.846, 34.984
Zone Results	Nu EDSU	37.009, 34.927
Zone Results	Deviation Zu	8.53%, 10.06%
Zone Results	Deviation HEDH	7.75%, 8.56%
Zone Results	Deviation EDSU	8.15%, 8.41%
Zone Results	Pressure Drop (Zukauskas)	2159.162 Pa, 748.579 Pa
Zone Results	Pressure Drop	1937.742 Pa, 831.104 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	10.25%, 11.02%

Table A.8: Results for Sl125 St16 16 case

A.9 Results for Sl125 St16 case

Section	Key	Value
Overall Results	Total Pressure Drop	4644.632 Pa
Overall Results	Total Heat Transfer	340.293 kW
Overall Results	Mean HTC (CFD)	226.073 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	35.137
Overall Results	Total Number of Tubes	832.0
Overall Results	Total Heat Transfer (Pipe) Area	13.069 m ²
Overall Results	Average Nu Deviation (Zu)	10.72%
Overall Results	Average Nu Deviation (HEDH)	8.96%
Overall Results	Average Nu Deviation (EDSU)	9.84%
Overall Results	Average dP Deviation	23.34%
Overall Results	HT/dP Ratio	73.27
Zone Results	Nu CFD	35.137
Zone Results	Nu Zukauskas	39.358
Zone Results	Nu HEDH	38.596
Zone Results	Nu EDSU	38.970
Zone Results	Deviation Zu	10.72%
Zone Results	Deviation HEDH	8.96%
Zone Results	Deviation EDSU	9.84%
Zone Results	Pressure Drop (Zukauskas)	3765.719 Pa
Zone Results	Pressure Drop	4644.632 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	23.34%

Table A.9: Results for Sl125 St16 case

A.10 Results for S1125 St18 18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1943.503 Pa
Overall Results	Total Heat Transfer	330.462 kW
Overall Results	Mean HTC (CFD)	213.985 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.525
Overall Results	Total Number of Tubes	752.0
Overall Results	Total Heat Transfer (Pipe) Area	11.812 m ²
Overall Results	Average Nu Deviation (Zu)	2.28%
Overall Results	Average Nu Deviation (HEDH)	6.31%
Overall Results	Average Nu Deviation (EDSU)	4.81%
Overall Results	Average dP Deviation	10.13%
Overall Results	HT/dP Ratio	170.03
Zone Results	Nu CFD	30.214, 31.294, 30.797, 28.924
Zone Results	Nu Zukauskas	28.841, 30.816, 31.172, 29.398
Zone Results	Nu HEDH	31.850, 32.984, 33.162, 31.384
Zone Results	Nu EDSU	30.772, 32.734, 32.932, 30.946
Zone Results	Deviation Zu	4.76%, 1.55%, 1.20%, 1.61%
Zone Results	Deviation HEDH	5.14%, 5.12%, 7.13%, 7.84%
Zone Results	Deviation EDSU	1.81%, 4.40%, 6.48%, 6.53%
Zone Results	Pressure Drop (Zukauskas)	933.078 Pa, 567.207 Pa, 382.917 Pa, 251.860 Pa
Zone Results	Pressure Drop	773.829 Pa, 511.823 Pa, 376.036 Pa, 281.815 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	17.07%, 9.76%, 1.80%, 11.89%

Table A.10: Results for S1125 St18 18 18 18 case

A.11 Results for S1125 St18 18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1931.179 Pa
Overall Results	Total Heat Transfer	330.681 kW
Overall Results	Mean HTC (CFD)	212.872 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.442
Overall Results	Total Number of Tubes	759.0
Overall Results	Total Heat Transfer (Pipe) Area	11.922 m ²
Overall Results	Average Nu Deviation (Zu)	1.94%
Overall Results	Average Nu Deviation (HEDH)	5.35%
Overall Results	Average Nu Deviation (EDSU)	4.24%
Overall Results	Average dP Deviation	9.89%
Overall Results	HT/dP Ratio	171.23
Zone Results	Nu CFD	30.388, 31.185, 29.120
Zone Results	Nu Zukauskas	29.241, 31.027, 29.531
Zone Results	Nu HEDH	31.635, 32.836, 31.344
Zone Results	Nu EDSU	31.227, 32.570, 30.902
Zone Results	Deviation Zu	3.92%, 0.51%, 1.39%
Zone Results	Deviation HEDH	3.94%, 5.03%, 7.09%
Zone Results	Deviation EDSU	2.69%, 4.25%, 5.77%
Zone Results	Pressure Drop (Zukauskas)	1137.976 Pa, 613.315 Pa, 356.115 Pa
Zone Results	Pressure Drop	963.540 Pa, 579.879 Pa, 387.760 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	15.33%, 5.45%, 8.89%

Table A.11: Results for S1125 St18 18 18 18 case

A.12 Results for S1125 St23 18 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	3128.845 Pa
Overall Results	Total Heat Transfer	339.801 kW
Overall Results	Mean HTC (CFD)	224.978 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.326
Overall Results	Total Number of Tubes	836.0
Overall Results	Total Heat Transfer (Pipe) Area	13.132 m ²
Overall Results	Average Nu Deviation (Zu)	3.05%
Overall Results	Average Nu Deviation (HEDH)	6.99%
Overall Results	Average Nu Deviation (EDSU)	8.20%
Overall Results	Average dP Deviation	17.09%
Overall Results	HT/dP Ratio	108.60
Zone Results	Nu CFD	28.196, 28.900, 38.382
Zone Results	Nu Zukauskas	26.703, 28.922, 39.769
Zone Results	Nu HEDH	27.813, 30.745, 44.413
Zone Results	Nu EDSU	26.978, 30.234, 45.518
Zone Results	Deviation Zu	5.59%, 0.08%, 3.49%
Zone Results	Deviation HEDH	1.38%, 6.00%, 13.58%
Zone Results	Deviation EDSU	4.52%, 4.41%, 15.68%
Zone Results	Pressure Drop (Zukauskas)	819.335 Pa, 586.387 Pa, 1198.956 Pa
Zone Results	Pressure Drop	953.992 Pa, 577.115 Pa, 1597.738 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	16.43%, 1.58%, 33.26%

Table A.12: Results for S1125 St23 18 13 case

A.13 Results for S1125 St25 18 16 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2687.740 Pa
Overall Results	Total Heat Transfer	337.688 kW
Overall Results	Mean HTC (CFD)	222.803 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.912
Overall Results	Total Number of Tubes	816.0
Overall Results	Total Heat Transfer (Pipe) Area	12.818 m ²
Overall Results	Average Nu Deviation (Zu)	3.76%
Overall Results	Average Nu Deviation (HEDH)	7.66%
Overall Results	Average Nu Deviation (EDSU)	9.12%
Overall Results	Average dP Deviation	11.93%
Overall Results	HT/dP Ratio	125.64
Zone Results	Nu CFD	27.604, 29.707, 30.618, 37.157
Zone Results	Nu Zukauskas	26.300, 29.116, 32.029, 38.561
Zone Results	Nu HEDH	27.608, 31.274, 34.761, 43.049
Zone Results	Nu EDSU	26.162, 30.823, 34.715, 43.991
Zone Results	Deviation Zu	4.96%, 2.03%, 4.41%, 3.64%
Zone Results	Deviation HEDH	0.02%, 5.01%, 11.92%, 13.69%
Zone Results	Deviation EDSU	5.51%, 3.62%, 11.80%, 15.53%
Zone Results	Pressure Drop (Zukauskas)	634.201 Pa, 567.614 Pa, 496.572 Pa, 743.532 Pa
Zone Results	Pressure Drop	693.793 Pa, 553.942 Pa, 469.725 Pa, 970.280 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	9.40%, 2.41%, 5.41%, 30.50%

Table A.13: Results for S1125 St25 18 16 13 case

A.14 Results for S1125 St27 2 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2962.037 Pa
Overall Results	Total Heat Transfer	337.473 kW
Overall Results	Mean HTC (CFD)	222.990 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.382
Overall Results	Total Number of Tubes	792.0
Overall Results	Total Heat Transfer (Pipe) Area	12.441 m ²
Overall Results	Average Nu Deviation (Zu)	1.59%
Overall Results	Average Nu Deviation (HEDH)	5.68%
Overall Results	Average Nu Deviation (EDSU)	6.70%
Overall Results	Average dP Deviation	14.53%
Overall Results	HT/dP Ratio	113.93
Zone Results	Nu CFD	27.035, 27.357, 38.550
Zone Results	Nu Zukauskas	26.491, 27.187, 39.372
Zone Results	Nu HEDH	26.889, 28.537, 43.988
Zone Results	Nu EDSU	25.956, 27.778, 45.043
Zone Results	Deviation Zu	2.05%, 0.62%, 2.09%
Zone Results	Deviation HEDH	0.54%, 4.14%, 12.36%
Zone Results	Deviation EDSU	4.16%, 1.52%, 14.41%
Zone Results	Pressure Drop (Zukauskas)	755.204 Pa, 510.106 Pa, 1226.140 Pa
Zone Results	Pressure Drop	765.310 Pa, 551.115 Pa, 1645.612 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	1.34%, 8.04%, 34.21%

Table A.14: Results for S1125 St27 2 13 case

A.15 Results for Sl125 St2 15 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	3425.912 Pa
Overall Results	Total Heat Transfer	343.781 kW
Overall Results	Mean HTC (CFD)	231.158 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	33.227
Overall Results	Total Number of Tubes	913.0
Overall Results	Total Heat Transfer (Pipe) Area	14.341 m ²
Overall Results	Average Nu Deviation (Zu)	4.22%
Overall Results	Average Nu Deviation (HEDH)	8.66%
Overall Results	Average Nu Deviation (EDSU)	9.91%
Overall Results	Average dP Deviation	13.09%
Overall Results	HT/dP Ratio	100.35
Zone Results	Nu CFD	29.012, 33.696, 38.487
Zone Results	Nu Zukauskas	27.475, 34.456, 40.451
Zone Results	Nu HEDH	29.231, 37.638, 45.143
Zone Results	Nu EDSU	28.551, 37.935, 46.337
Zone Results	Deviation Zu	5.59%, 2.21%, 4.86%
Zone Results	Deviation HEDH	0.75%, 10.47%, 14.75%
Zone Results	Deviation EDSU	1.61%, 11.18%, 16.94%
Zone Results	Pressure Drop (Zukauskas)	926.570 Pa, 1001.598 Pa, 1153.481 Pa
Zone Results	Pressure Drop	905.653 Pa, 972.876 Pa, 1547.384 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	2.26%, 2.87%, 34.15%

Table A.15: Results for Sl125 St2 15 13 case

A.16 Results for Sl125 St2 17 14 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	3065.497 Pa
Overall Results	Total Heat Transfer	342.308 kW
Overall Results	Mean HTC (CFD)	230.604 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	32.963
Overall Results	Total Number of Tubes	880.0
Overall Results	Total Heat Transfer (Pipe) Area	13.823 m ²
Overall Results	Average Nu Deviation (Zu)	4.66%
Overall Results	Average Nu Deviation (HEDH)	9.21%
Overall Results	Average Nu Deviation (EDSU)	9.86%
Overall Results	Average dP Deviation	11.46%
Overall Results	HT/dP Ratio	111.66
Zone Results	Nu CFD	28.826, 31.706, 35.642, 37.285
Zone Results	Nu Zukauskas	27.200, 31.002, 37.821, 39.098
Zone Results	Nu HEDH	29.531, 33.452, 41.780, 43.621
Zone Results	Nu EDSU	28.247, 33.255, 42.573, 44.632
Zone Results	Deviation Zu	5.98%, 2.27%, 5.76%, 4.64%
Zone Results	Deviation HEDH	2.39%, 5.22%, 14.69%, 14.53%
Zone Results	Deviation EDSU	2.05%, 4.66%, 16.28%, 16.46%
Zone Results	Pressure Drop (Zukauskas)	759.418 Pa, 629.810 Pa, 833.116 Pa, 723.153 Pa
Zone Results	Pressure Drop	715.566 Pa, 573.960 Pa, 829.863 Pa, 946.108 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	5.77%, 8.87%, 0.39%, 30.83%

Table A.16: Results for Sl125 St2 17 14 13 case

A.17 Results for Sl125 St2 2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	1706.504 Pa
Overall Results	Total Heat Transfer	321.461 kW
Overall Results	Mean HTC (CFD)	210.740 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.265
Overall Results	Total Number of Tubes	672.0
Overall Results	Total Heat Transfer (Pipe) Area	10.556 m ²
Overall Results	Average Nu Deviation (Zu)	2.71%
Overall Results	Average Nu Deviation (HEDH)	3.31%
Overall Results	Average Nu Deviation (EDSU)	2.29%
Overall Results	Average dP Deviation	6.68%
Overall Results	HT/dP Ratio	188.37
Zone Results	Nu CFD	29.089, 29.753, 29.388, 28.008
Zone Results	Nu Zukauskas	27.212, 28.842, 29.411, 28.207
Zone Results	Nu HEDH	29.543, 30.451, 30.661, 29.567
Zone Results	Nu EDSU	28.260, 29.908, 30.144, 28.924
Zone Results	Deviation Zu	6.90%, 3.16%, 0.08%, 0.71%
Zone Results	Deviation HEDH	1.54%, 2.29%, 4.15%, 5.27%
Zone Results	Deviation EDSU	2.94%, 0.52%, 2.51%, 3.17%
Zone Results	Pressure Drop (Zukauskas)	759.952 Pa, 482.825 Pa, 328.296 Pa, 224.795 Pa
Zone Results	Pressure Drop	720.629 Pa, 440.811 Pa, 306.399 Pa, 238.665 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	5.17%, 8.70%, 6.67%, 6.17%

Table A.17: Results for Sl125 St2 2 2 2 case

A.18 Results for Sl125 St2 2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	1732.775 Pa
Overall Results	Total Heat Transfer	322.240 kW
Overall Results	Mean HTC (CFD)	209.823 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.227
Overall Results	Total Number of Tubes	682.0
Overall Results	Total Heat Transfer (Pipe) Area	10.713 m ²
Overall Results	Average Nu Deviation (Zu)	3.30%
Overall Results	Average Nu Deviation (HEDH)	2.41%
Overall Results	Average Nu Deviation (EDSU)	1.70%
Overall Results	Average dP Deviation	3.66%
Overall Results	HT/dP Ratio	185.97
Zone Results	Nu CFD	29.023, 30.045, 28.055
Zone Results	Nu Zukauskas	27.423, 29.224, 28.410
Zone Results	Nu HEDH	29.179, 30.521, 29.576
Zone Results	Nu EDSU	28.493, 29.988, 28.935
Zone Results	Deviation Zu	5.84%, 2.81%, 1.25%
Zone Results	Deviation HEDH	0.53%, 1.56%, 5.14%
Zone Results	Deviation EDSU	1.86%, 0.19%, 3.04%
Zone Results	Pressure Drop (Zukauskas)	923.165 Pa, 536.370 Pa, 318.938 Pa
Zone Results	Pressure Drop	914.713 Pa, 492.912 Pa, 325.150 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	0.92%, 8.10%, 1.95%

Table A.18: Results for Sl125 St2 2 2 2 case

A.19 Results for Sl125 St3 2 17 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2186.872 Pa
Overall Results	Total Heat Transfer	333.218 kW
Overall Results	Mean HTC (CFD)	214.833 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	28.790
Overall Results	Total Number of Tubes	760.0
Overall Results	Total Heat Transfer (Pipe) Area	11.938 m ²
Overall Results	Average Nu Deviation (Zu)	4.19%
Overall Results	Average Nu Deviation (HEDH)	8.38%
Overall Results	Average Nu Deviation (EDSU)	6.45%
Overall Results	Average dP Deviation	19.99%
Overall Results	HT/dP Ratio	152.37
Zone Results	Nu CFD	23.520, 27.952, 29.063, 37.008
Zone Results	Nu Zukauskas	25.776, 27.045, 29.656, 38.017
Zone Results	Nu HEDH	25.926, 28.681, 31.888, 42.469
Zone Results	Nu EDSU	24.343, 27.937, 31.506, 43.340
Zone Results	Deviation Zu	8.75%, 3.35%, 2.00%, 2.65%
Zone Results	Deviation HEDH	9.28%, 2.54%, 8.86%, 12.86%
Zone Results	Deviation EDSU	3.38%, 0.05%, 7.75%, 14.61%
Zone Results	Pressure Drop (Zukauskas)	534.948 Pa, 497.754 Pa, 425.366 Pa, 759.198 Pa
Zone Results	Pressure Drop	323.765 Pa, 486.879 Pa, 389.807 Pa, 986.421 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	39.48%, 2.18%, 8.36%, 29.93%

Table A.19: Results for Sl125 St3 2 17 13 case

A.20 Results for Sl15 St13 13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	6554.794 Pa
Overall Results	Total Heat Transfer	345.198 kW
Overall Results	Mean HTC (CFD)	257.193 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	39.638
Overall Results	Total Number of Tubes	858.0
Overall Results	Total Heat Transfer (Pipe) Area	13.477 m ²
Overall Results	Average Nu Deviation (Zu)	6.17%
Overall Results	Average Nu Deviation (HEDH)	15.73%
Overall Results	Average Nu Deviation (EDSU)	17.29%
Overall Results	Average dP Deviation	12.73%
Overall Results	HT/dP Ratio	52.66
Zone Results	Nu CFD	41.818, 39.946, 38.646, 35.254
Zone Results	Nu Zukauskas	40.757, 42.806, 42.002, 38.079
Zone Results	Nu HEDH	47.449, 48.113, 46.650, 42.441
Zone Results	Nu EDSU	47.223, 49.666, 48.026, 43.309
Zone Results	Deviation Zu	2.60%, 6.68%, 7.99%, 7.42%
Zone Results	Deviation HEDH	11.87%, 16.97%, 17.16%, 16.93%
Zone Results	Deviation EDSU	11.44%, 19.57%, 19.53%, 18.60%
Zone Results	Pressure Drop (Zukauskas)	2883.454 Pa, 1430.332 Pa, 915.422 Pa, 586.946 Pa
Zone Results	Pressure Drop	3261.772 Pa, 1603.681 Pa, 1016.567 Pa, 672.774 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	13.12%, 12.12%, 11.05%, 14.62%

Table A.20: Results for Sl15 St13 13 13 13 case

A.21 Results for Sl15 St13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	9231.229 Pa
Overall Results	Total Heat Transfer	346.404 kW
Overall Results	Mean HTC (CFD)	263.675 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	41.199
Overall Results	Total Number of Tubes	873.0
Overall Results	Total Heat Transfer (Pipe) Area	13.713 m ²
Overall Results	Average Nu Deviation (Zu)	6.14%
Overall Results	Average Nu Deviation (HEDH)	16.72%
Overall Results	Average Nu Deviation (EDSU)	19.03%
Overall Results	Average dP Deviation	32.53%
Overall Results	HT/dP Ratio	37.53
Zone Results	Nu CFD	43.820, 40.220, 37.709
Zone Results	Nu Zukauskas	43.858, 44.319, 41.482
Zone Results	Nu HEDH	50.372, 49.384, 46.324
Zone Results	Nu EDSU	51.514, 51.086, 47.658
Zone Results	Deviation Zu	0.09%, 9.25%, 9.09%
Zone Results	Deviation HEDH	13.01%, 18.56%, 18.60%
Zone Results	Deviation EDSU	14.94%, 21.27%, 20.88%
Zone Results	Pressure Drop (Zukauskas)	4200.057 Pa, 1737.214 Pa, 1097.170 Pa
Zone Results	Pressure Drop	5543.341 Pa, 2099.659 Pa, 1588.229 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	31.98%, 20.86%, 44.76%

Table A.21: Results for Sl15 St13 13 13 case

A.22 Results for Sl15 St14 14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	3639.579 Pa
Overall Results	Total Heat Transfer	340.112 kW
Overall Results	Mean HTC (CFD)	238.447 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	35.608
Overall Results	Total Number of Tubes	804.0
Overall Results	Total Heat Transfer (Pipe) Area	12.629 m ²
Overall Results	Average Nu Deviation (Zu)	5.99%
Overall Results	Average Nu Deviation (HEDH)	13.93%
Overall Results	Average Nu Deviation (EDSU)	14.49%
Overall Results	Average dP Deviation	4.16%
Overall Results	HT/dP Ratio	93.45
Zone Results	Nu CFD	37.088, 35.862, 34.856, 32.302
Zone Results	Nu Zukauskas	35.453, 37.636, 37.693, 34.777
Zone Results	Nu HEDH	40.815, 41.905, 41.525, 38.505
Zone Results	Nu EDSU	40.051, 42.715, 42.288, 38.901
Zone Results	Deviation Zu	4.61%, 4.71%, 7.53%, 7.12%
Zone Results	Deviation HEDH	9.13%, 14.42%, 16.06%, 16.11%
Zone Results	Deviation EDSU	7.40%, 16.04%, 17.57%, 16.96%
Zone Results	Pressure Drop (Zukauskas)	1780.857 Pa, 973.588 Pa, 642.473 Pa, 414.553 Pa
Zone Results	Pressure Drop	1632.757 Pa, 936.280 Pa, 639.377 Pa, 431.165 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	8.32%, 3.83%, 0.48%, 4.01%

Table A.22: Results for Sl15 St14 14 14 14 case

A.23 Results for Sl15 St14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	4285.838 Pa
Overall Results	Total Heat Transfer	341.236 kW
Overall Results	Mean HTC (CFD)	242.204 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	36.572
Overall Results	Total Number of Tubes	810.0
Overall Results	Total Heat Transfer (Pipe) Area	12.723 m ²
Overall Results	Average Nu Deviation (Zu)	4.09%
Overall Results	Average Nu Deviation (HEDH)	13.52%
Overall Results	Average Nu Deviation (EDSU)	14.73%
Overall Results	Average dP Deviation	7.28%
Overall Results	HT/dP Ratio	79.62
Zone Results	Nu CFD	37.869, 36.958, 33.493
Zone Results	Nu Zukauskas	37.556, 38.883, 35.821
Zone Results	Nu HEDH	42.668, 42.947, 39.577
Zone Results	Nu EDSU	43.002, 43.882, 40.104
Zone Results	Deviation Zu	0.83%, 4.95%, 6.50%
Zone Results	Deviation HEDH	11.25%, 13.95%, 15.37%
Zone Results	Deviation EDSU	11.94%, 15.78%, 16.48%
Zone Results	Pressure Drop (Zukauskas)	2423.332 Pa, 1112.914 Pa, 606.818 Pa
Zone Results	Pressure Drop	2418.032 Pa, 1149.986 Pa, 717.819 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	0.22%, 3.33%, 18.29%

Table A.23: Results for Sl15 St14 14 14 case

A.24 Results for S115 St16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	2224.323 Pa
Overall Results	Total Heat Transfer	328.831 kW
Overall Results	Mean HTC (CFD)	219.305 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.469
Overall Results	Total Number of Tubes	711.0
Overall Results	Total Heat Transfer (Pipe) Area	11.168 m ²
Overall Results	Average Nu Deviation (Zu)	5.01%
Overall Results	Average Nu Deviation (HEDH)	11.07%
Overall Results	Average Nu Deviation (EDSU)	10.58%
Overall Results	Average dP Deviation	9.95%
Overall Results	HT/dP Ratio	147.83
Zone Results	Nu CFD	33.119, 30.779, 29.211
Zone Results	Nu Zukauskas	31.921, 32.406, 31.157
Zone Results	Nu HEDH	35.639, 35.114, 33.880
Zone Results	Nu EDSU	35.234, 35.111, 33.730
Zone Results	Deviation Zu	3.75%, 5.02%, 6.25%
Zone Results	Deviation HEDH	7.07%, 12.35%, 13.78%
Zone Results	Deviation EDSU	6.00%, 12.34%, 13.40%
Zone Results	Pressure Drop (Zukauskas)	1387.194 Pa, 646.711 Pa, 390.709 Pa
Zone Results	Pressure Drop	1198.428 Pa, 599.993 Pa, 425.901 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	13.61%, 7.22%, 9.01%

Table A.24: Results for S115 St16 16 16 case

A.25 Results for S115 St18 18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1609.069 Pa
Overall Results	Total Heat Transfer	315.471 kW
Overall Results	Mean HTC (CFD)	208.879 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	28.792
Overall Results	Total Number of Tubes	630.0
Overall Results	Total Heat Transfer (Pipe) Area	9.896 m ²
Overall Results	Average Nu Deviation (Zu)	6.59%
Overall Results	Average Nu Deviation (HEDH)	10.54%
Overall Results	Average Nu Deviation (EDSU)	8.70%
Overall Results	Average dP Deviation	14.22%
Overall Results	HT/dP Ratio	196.06
Zone Results	Nu CFD	30.386, 29.061, 27.757, 25.954
Zone Results	Nu Zukauskas	28.509, 29.962, 30.289, 28.329
Zone Results	Nu HEDH	31.746, 32.234, 32.202, 30.270
Zone Results	Nu EDSU	30.261, 31.895, 31.859, 29.703
Zone Results	Deviation Zu	6.59%, 3.01%, 8.36%, 8.38%
Zone Results	Deviation HEDH	4.28%, 9.84%, 13.80%, 14.26%
Zone Results	Deviation EDSU	0.41%, 8.88%, 12.88%, 12.62%
Zone Results	Pressure Drop (Zukauskas)	831.058 Pa, 506.050 Pa, 341.918 Pa, 219.928 Pa
Zone Results	Pressure Drop	699.475 Pa, 413.317 Pa, 298.242 Pa, 198.035 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	15.83%, 18.32%, 12.77%, 9.95%

Table A.25: Results for S115 St18 18 18 18 case

A.26 Results for Sl15 St18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1553.175 Pa
Overall Results	Total Heat Transfer	313.992 kW
Overall Results	Mean HTC (CFD)	208.171 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	28.583
Overall Results	Total Number of Tubes	621.0
Overall Results	Total Heat Transfer (Pipe) Area	9.755 m ²
Overall Results	Average Nu Deviation (Zu)	5.81%
Overall Results	Average Nu Deviation (HEDH)	9.46%
Overall Results	Average Nu Deviation (EDSU)	7.66%
Overall Results	Average dP Deviation	11.78%
Overall Results	HT/dP Ratio	202.16
Zone Results	Nu CFD	29.849, 28.463, 26.322
Zone Results	Nu Zukauskas	28.517, 29.710, 28.784
Zone Results	Nu HEDH	31.174, 31.623, 30.654
Zone Results	Nu EDSU	30.313, 31.214, 30.132
Zone Results	Deviation Zu	4.67%, 4.20%, 8.55%
Zone Results	Deviation HEDH	4.25%, 9.99%, 14.13%
Zone Results	Deviation EDSU	1.53%, 8.81%, 12.64%
Zone Results	Pressure Drop (Zukauskas)	954.024 Pa, 525.796 Pa, 314.018 Pa
Zone Results	Pressure Drop	814.419 Pa, 436.395 Pa, 302.361 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	14.63%, 17.00%, 3.71%

Table A.26: Results for Sl15 St18 18 18 case

A.27 Results for S115 St23 18 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2642.291 Pa
Overall Results	Total Heat Transfer	330.201 kW
Overall Results	Mean HTC (CFD)	225.545 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.262
Overall Results	Total Number of Tubes	684.0
Overall Results	Total Heat Transfer (Pipe) Area	10.744 m ²
Overall Results	Average Nu Deviation (Zu)	2.58%
Overall Results	Average Nu Deviation (HEDH)	7.70%
Overall Results	Average Nu Deviation (EDSU)	7.93%
Overall Results	Average dP Deviation	19.82%
Overall Results	HT/dP Ratio	124.97
Zone Results	Nu CFD	26.478, 28.292, 37.587
Zone Results	Nu Zukauskas	25.674, 28.268, 39.370
Zone Results	Nu HEDH	27.054, 30.190, 44.057
Zone Results	Nu EDSU	25.796, 29.614, 45.119
Zone Results	Deviation Zu	3.13%, 0.09%, 4.53%
Zone Results	Deviation HEDH	2.13%, 6.29%, 14.69%
Zone Results	Deviation EDSU	2.64%, 4.47%, 16.69%
Zone Results	Pressure Drop (Zukauskas)	653.690 Pa, 526.695 Pa, 1082.722 Pa
Zone Results	Pressure Drop	595.887 Pa, 490.340 Pa, 1556.065 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	8.84%, 6.90%, 43.72%

Table A.27: Results for S115 St23 18 13 case

A.28 Results for S115 St25 18 16 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	1977.132 Pa
Overall Results	Total Heat Transfer	326.356 kW
Overall Results	Mean HTC (CFD)	220.160 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.484
Overall Results	Total Number of Tubes	676.0
Overall Results	Total Heat Transfer (Pipe) Area	10.619 m ²
Overall Results	Average Nu Deviation (Zu)	3.28%
Overall Results	Average Nu Deviation (HEDH)	8.04%
Overall Results	Average Nu Deviation (EDSU)	8.34%
Overall Results	Average dP Deviation	10.85%
Overall Results	HT/dP Ratio	165.07
Zone Results	Nu CFD	25.911, 28.989, 29.920, 34.932
Zone Results	Nu Zukauskas	25.067, 28.221, 30.848, 36.401
Zone Results	Nu HEDH	26.607, 30.479, 33.469, 40.657
Zone Results	Nu EDSU	24.750, 29.936, 33.271, 41.309
Zone Results	Deviation Zu	3.37%, 2.72%, 3.01%, 4.03%
Zone Results	Deviation HEDH	2.61%, 4.89%, 10.60%, 14.08%
Zone Results	Deviation EDSU	4.69%, 3.16%, 10.07%, 15.44%
Zone Results	Pressure Drop (Zukauskas)	512.078 Pa, 504.221 Pa, 427.124 Pa, 589.392 Pa
Zone Results	Pressure Drop	446.758 Pa, 457.903 Pa, 397.507 Pa, 674.964 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	12.76%, 9.19%, 6.93%, 14.52%

Table A.28: Results for S115 St25 18 16 13 case

A.29 Results for S115 St27 2 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2575.226 Pa
Overall Results	Total Heat Transfer	326.726 kW
Overall Results	Mean HTC (CFD)	223.370 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.306
Overall Results	Total Number of Tubes	648.0
Overall Results	Total Heat Transfer (Pipe) Area	10.179 m ²
Overall Results	Average Nu Deviation (Zu)	1.84%
Overall Results	Average Nu Deviation (HEDH)	6.56%
Overall Results	Average Nu Deviation (EDSU)	6.80%
Overall Results	Average dP Deviation	20.54%
Overall Results	HT/dP Ratio	126.87
Zone Results	Nu CFD	25.248, 26.956, 37.527
Zone Results	Nu Zukauskas	25.041, 26.625, 38.863
Zone Results	Nu HEDH	25.749, 28.077, 43.512
Zone Results	Nu EDSU	24.373, 27.266, 44.508
Zone Results	Deviation Zu	0.83%, 1.24%, 3.44%
Zone Results	Deviation HEDH	1.95%, 3.99%, 13.75%
Zone Results	Deviation EDSU	3.59%, 1.13%, 15.69%
Zone Results	Pressure Drop (Zukauskas)	579.897 Pa, 456.853 Pa, 1109.212 Pa
Zone Results	Pressure Drop	520.580 Pa, 433.087 Pa, 1621.559 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	10.23%, 5.20%, 46.19%

Table A.29: Results for S115 St27 2 13 case

A.30 Results for S115 St2 15 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	3056.384 Pa
Overall Results	Total Heat Transfer	336.483 kW
Overall Results	Mean HTC (CFD)	233.580 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	32.476
Overall Results	Total Number of Tubes	747.0
Overall Results	Total Heat Transfer (Pipe) Area	11.734 m ²
Overall Results	Average Nu Deviation (Zu)	4.14%
Overall Results	Average Nu Deviation (HEDH)	10.05%
Overall Results	Average Nu Deviation (EDSU)	10.04%
Overall Results	Average dP Deviation	20.64%
Overall Results	HT/dP Ratio	110.09
Zone Results	Nu CFD	28.040, 33.298, 37.435
Zone Results	Nu Zukauskas	26.959, 33.817, 40.202
Zone Results	Nu HEDH	28.973, 37.090, 44.949
Zone Results	Nu EDSU	27.897, 37.321, 46.119
Zone Results	Deviation Zu	4.01%, 1.54%, 6.88%
Zone Results	Deviation HEDH	3.22%, 10.22%, 16.72%
Zone Results	Deviation EDSU	0.51%, 10.78%, 18.83%
Zone Results	Pressure Drop (Zukauskas)	784.648 Pa, 904.765 Pa, 1031.613 Pa
Zone Results	Pressure Drop	683.999 Pa, 871.947 Pa, 1500.437 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	12.83%, 3.63%, 45.45%

Table A.30: Results for S115 St2 15 13 case

A.31 Results for S115 St2 17 14 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2384.501 Pa
Overall Results	Total Heat Transfer	333.493 kW
Overall Results	Mean HTC (CFD)	227.947 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.516
Overall Results	Total Number of Tubes	732.0
Overall Results	Total Heat Transfer (Pipe) Area	11.498 m ²
Overall Results	Average Nu Deviation (Zu)	4.09%
Overall Results	Average Nu Deviation (HEDH)	10.10%
Overall Results	Average Nu Deviation (EDSU)	9.79%
Overall Results	Average dP Deviation	11.36%
Overall Results	HT/dP Ratio	139.86
Zone Results	Nu CFD	28.027, 30.122, 34.800, 34.486
Zone Results	Nu Zukauskas	26.761, 29.784, 36.137, 36.994
Zone Results	Nu HEDH	29.306, 32.325, 39.892, 41.287
Zone Results	Nu EDSU	27.639, 31.995, 40.457, 42.016
Zone Results	Deviation Zu	4.73%, 1.14%, 3.70%, 6.78%
Zone Results	Deviation HEDH	4.37%, 6.81%, 12.76%, 16.47%
Zone Results	Deviation EDSU	1.40%, 5.85%, 13.98%, 17.92%
Zone Results	Pressure Drop (Zukauskas)	670.041 Pa, 546.511 Pa, 694.420 Pa, 568.604 Pa
Zone Results	Pressure Drop	554.042 Pa, 478.129 Pa, 697.276 Pa, 655.053 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	17.31%, 12.51%, 0.41%, 15.20%

Table A.31: Results for S115 St2 17 14 13 case

A.32 Results for Sl15 St2 18 16 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	1850.006 Pa
Overall Results	Total Heat Transfer	325.627 kW
Overall Results	Mean HTC (CFD)	217.658 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.698
Overall Results	Total Number of Tubes	685.0
Overall Results	Total Heat Transfer (Pipe) Area	10.760 m ²
Overall Results	Average Nu Deviation (Zu)	6.23%
Overall Results	Average Nu Deviation (HEDH)	9.06%
Overall Results	Average Nu Deviation (EDSU)	8.02%
Overall Results	Average dP Deviation	10.14%
Overall Results	HT/dP Ratio	176.01
Zone Results	Nu CFD	28.096, 28.843, 30.016, 32.270
Zone Results	Nu Zukauskas	28.373, 30.407, 33.079, 35.682
Zone Results	Nu HEDH	29.347, 30.985, 33.875, 37.385
Zone Results	Nu EDSU	27.668, 30.482, 33.704, 37.623
Zone Results	Deviation Zu	0.98%, 5.14%, 9.26%, 9.56%
Zone Results	Deviation HEDH	4.26%, 6.91%, 11.39%, 13.68%
Zone Results	Deviation EDSU	1.55%, 5.38%, 10.94%, 14.23%
Zone Results	Pressure Drop (Zukauskas)	680.218 Pa, 490.019 Pa, 419.413 Pa, 424.142 Pa
Zone Results	Pressure Drop	563.549 Pa, 439.229 Pa, 393.757 Pa, 453.472 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	17.15%, 10.37%, 6.12%, 6.92%

Table A.32: Results for Sl15 St2 18 16 14 case

A.33 Results for Sl15 St2 2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	1306.183 Pa
Overall Results	Total Heat Transfer	302.530 kW
Overall Results	Mean HTC (CFD)	203.565 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.179
Overall Results	Total Number of Tubes	563.0
Overall Results	Total Heat Transfer (Pipe) Area	8.844 m ²
Overall Results	Average Nu Deviation (Zu)	3.90%
Overall Results	Average Nu Deviation (HEDH)	6.78%
Overall Results	Average Nu Deviation (EDSU)	4.79%
Overall Results	Average dP Deviation	15.40%
Overall Results	HT/dP Ratio	231.61
Zone Results	Nu CFD	28.428, 27.381, 26.200, 25.100
Zone Results	Nu Zukauskas	26.794, 27.358, 27.209, 26.614
Zone Results	Nu HEDH	29.341, 29.085, 28.449, 27.970
Zone Results	Nu EDSU	27.676, 28.388, 27.681, 27.147
Zone Results	Deviation Zu	6.10%, 0.09%, 3.71%, 5.69%
Zone Results	Deviation HEDH	3.11%, 5.86%, 7.90%, 10.26%
Zone Results	Deviation EDSU	2.72%, 3.55%, 5.35%, 7.54%
Zone Results	Pressure Drop (Zukauskas)	672.578 Pa, 406.871 Pa, 259.542 Pa, 187.516 Pa
Zone Results	Pressure Drop	567.708 Pa, 370.001 Pa, 226.025 Pa, 142.449 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	15.59%, 9.06%, 12.91%, 24.03%

Table A.33: Results for Sl15 St2 2 2 2 case

A.34 Results for Sl15 St2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	1289.683 Pa
Overall Results	Total Heat Transfer	301.182 kW
Overall Results	Mean HTC (CFD)	203.061 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.100
Overall Results	Total Number of Tubes	558.0
Overall Results	Total Heat Transfer (Pipe) Area	8.765 m ²
Overall Results	Average Nu Deviation (Zu)	5.97%
Overall Results	Average Nu Deviation (HEDH)	7.74%
Overall Results	Average Nu Deviation (EDSU)	6.18%
Overall Results	Average dP Deviation	16.14%
Overall Results	HT/dP Ratio	233.53
Zone Results	Nu CFD	28.380, 27.266, 24.573
Zone Results	Nu Zukauskas	26.943, 27.848, 27.457
Zone Results	Nu HEDH	28.958, 29.269, 28.701
Zone Results	Nu EDSU	27.879, 28.592, 27.962
Zone Results	Deviation Zu	5.33%, 2.09%, 10.50%
Zone Results	Deviation HEDH	2.00%, 6.84%, 14.38%
Zone Results	Deviation EDSU	1.79%, 4.64%, 12.12%
Zone Results	Pressure Drop (Zukauskas)	784.460 Pa, 453.427 Pa, 278.017 Pa
Zone Results	Pressure Drop	689.309 Pa, 375.464 Pa, 224.910 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	12.13%, 17.19%, 19.10%

Table A.34: Results for Sl15 St2 2 2 case

A.35 Results for Sl15 St3 2 17 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	1728.701 Pa
Overall Results	Total Heat Transfer	319.731 kW
Overall Results	Mean HTC (CFD)	214.469 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.815
Overall Results	Total Number of Tubes	627.0
Overall Results	Total Heat Transfer (Pipe) Area	9.849 m ²
Overall Results	Average Nu Deviation (Zu)	3.71%
Overall Results	Average Nu Deviation (HEDH)	7.57%
Overall Results	Average Nu Deviation (EDSU)	6.20%
Overall Results	Average dP Deviation	16.06%
Overall Results	HT/dP Ratio	184.95
Zone Results	Nu CFD	23.305, 27.703, 27.760, 34.988
Zone Results	Nu Zukauskas	24.482, 26.417, 28.577, 35.806
Zone Results	Nu HEDH	24.905, 28.158, 30.725, 40.025
Zone Results	Nu EDSU	22.939, 27.356, 30.209, 40.601
Zone Results	Deviation Zu	4.81%, 4.87%, 2.86%, 2.29%
Zone Results	Deviation HEDH	6.42%, 1.61%, 9.65%, 12.59%
Zone Results	Deviation EDSU	1.60%, 1.27%, 8.11%, 13.83%
Zone Results	Pressure Drop (Zukauskas)	440.148 Pa, 437.899 Pa, 365.898 Pa, 607.166 Pa
Zone Results	Pressure Drop	292.106 Pa, 405.565 Pa, 334.679 Pa, 696.351 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	33.63%, 7.38%, 8.53%, 14.69%

Table A.35: Results for Sl15 St3 2 17 13 case

A.36 Results for Sl175 St13 13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	6240.545 Pa
Overall Results	Total Heat Transfer	340.354 kW
Overall Results	Mean HTC (CFD)	261.158 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	39.126
Overall Results	Total Number of Tubes	730.0
Overall Results	Total Heat Transfer (Pipe) Area	11.467 m ²
Overall Results	Average Nu Deviation (Zu)	6.12%
Overall Results	Average Nu Deviation (HEDH)	16.09%
Overall Results	Average Nu Deviation (EDSU)	17.16%
Overall Results	Average dP Deviation	19.81%
Overall Results	HT/dP Ratio	54.54
Zone Results	Nu CFD	41.170, 39.751, 38.168, 34.059
Zone Results	Nu Zukauskas	40.034, 41.900, 41.369, 37.328
Zone Results	Nu HEDH	47.223, 47.405, 46.075, 41.659
Zone Results	Nu EDSU	46.162, 48.872, 47.383, 42.432
Zone Results	Deviation Zu	2.84%, 5.13%, 7.74%, 8.76%
Zone Results	Deviation HEDH	12.82%, 16.15%, 17.16%, 18.24%
Zone Results	Deviation EDSU	10.81%, 18.66%, 19.45%, 19.73%
Zone Results	Pressure Drop (Zukauskas)	2580.973 Pa, 1308.399 Pa, 821.498 Pa, 497.273 Pa
Zone Results	Pressure Drop	3101.228 Pa, 1565.671 Pa, 970.295 Pa, 603.351 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	20.16%, 19.66%, 18.11%, 21.33%

Table A.36: Results for Sl175 St13 13 13 13 case

A.37 Results for Sl175 St13 13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	9639.127 Pa
Overall Results	Total Heat Transfer	341.413 kW
Overall Results	Mean HTC (CFD)	264.177 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	39.818
Overall Results	Total Number of Tubes	738.0
Overall Results	Total Heat Transfer (Pipe) Area	11.592 m ²
Overall Results	Average Nu Deviation (Zu)	16.14%
Overall Results	Average Nu Deviation (HEDH)	24.83%
Overall Results	Average Nu Deviation (EDSU)	27.00%
Overall Results	Average dP Deviation	44.40%
Overall Results	HT/dP Ratio	35.42
Zone Results	Nu CFD	41.525, 39.562, 36.196, 41.525, 39.562, 36.196
Zone Results	Nu Zukauskas	54.471, 51.824, 50.609, 42.962, 42.631, 40.391
Zone Results	Nu Grimison	65.842, 61.360, 59.878
Zone Results	Nu HEDH	61.196, 56.256, 54.834, 49.672, 47.652, 45.121
Zone Results	Nu EDSU	62.831, 58.747, 57.157, 50.275, 49.148, 46.311
Zone Results	Deviation Zu	23.77%, 23.66%, 28.48%, 3.34%, 7.20%, 10.39%
Zone Results	Deviation Grimison	36.93%, 35.53%, 39.55%
Zone Results	Deviation HEDH	32.14%, 29.68%, 33.99%, 16.40%, 16.98%, 19.78%
Zone Results	Deviation EDSU	33.91%, 32.66%, 36.67%, 17.40%, 19.51%, 21.84%
Zone Results	Pressure Drop (Zukauskas)	3774.699 Pa, 1498.811 Pa, 936.585 Pa, 3941.939 Pa, 1540.181 Pa, 962.937 Pa
Zone Results	Pressure Drop	6360.743 Pa, 1949.750 Pa, 1328.634 Pa, 6360.743 Pa, 1949.750 Pa, 1328.634 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	68.51%, 30.09%, 41.86%, 61.36%, 26.59%, 37.98%
Zone Results	Overall Results	
Zone Results	Total Pressure Drop	9639.127 Pa
Zone Results	Total Heat Transfer	341.413 kW
Zone Results	Mean HTC (CFD)	264.177 W/m ² K
Zone Results	Mean Nusselt Number (CFD)	39.818

Table A.37: Results for Sl175 St13 13 13 13 case

A.38 Results for S1175 St14 14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	3430.674 Pa
Overall Results	Total Heat Transfer	333.182 kW
Overall Results	Mean HTC (CFD)	242.456 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	35.176
Overall Results	Total Number of Tubes	684.0
Overall Results	Total Heat Transfer (Pipe) Area	10.744 m ²
Overall Results	Average Nu Deviation (Zu)	5.75%
Overall Results	Average Nu Deviation (HEDH)	14.12%
Overall Results	Average Nu Deviation (EDSU)	14.17%
Overall Results	Average dP Deviation	5.25%
Overall Results	HT/dP Ratio	97.12
Zone Results	Nu CFD	36.480, 35.762, 34.523, 31.264
Zone Results	Nu Zukauskas	34.778, 36.771, 37.046, 34.183
Zone Results	Nu HEDH	40.569, 41.222, 40.935, 37.899
Zone Results	Nu EDSU	39.094, 41.948, 41.626, 38.222
Zone Results	Deviation Zu	4.90%, 2.74%, 6.81%, 8.54%
Zone Results	Deviation HEDH	10.08%, 13.24%, 15.66%, 17.51%
Zone Results	Deviation EDSU	6.68%, 14.75%, 17.06%, 18.20%
Zone Results	Pressure Drop (Zukauskas)	1574.971 Pa, 883.561 Pa, 580.199 Pa, 360.883 Pa
Zone Results	Pressure Drop	1515.793 Pa, 914.568 Pa, 605.711 Pa, 394.602 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	3.76%, 3.51%, 4.40%, 9.34%

Table A.38: Results for S1175 St14 14 14 14 case

A.39 Results for S1175 St14 14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	3955.613 Pa
Overall Results	Total Heat Transfer	333.954 kW
Overall Results	Mean HTC (CFD)	244.635 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	35.816
Overall Results	Total Number of Tubes	685.0
Overall Results	Total Heat Transfer (Pipe) Area	10.760 m ²
Overall Results	Average Nu Deviation (Zu)	5.29%
Overall Results	Average Nu Deviation (HEDH)	14.06%
Overall Results	Average Nu Deviation (EDSU)	14.79%
Overall Results	Average dP Deviation	7.75%
Overall Results	HT/dP Ratio	84.43
Zone Results	Nu CFD	37.741, 35.352, 32.231
Zone Results	Nu Zukauskas	36.901, 37.632, 34.856
Zone Results	Nu HEDH	42.202, 41.705, 38.541
Zone Results	Nu EDSU	42.097, 42.490, 38.942
Zone Results	Deviation Zu	2.28%, 6.06%, 7.53%
Zone Results	Deviation HEDH	10.57%, 15.23%, 16.37%
Zone Results	Deviation EDSU	10.35%, 16.80%, 17.23%
Zone Results	Pressure Drop (Zukauskas)	2189.681 Pa, 982.745 Pa, 528.234 Pa
Zone Results	Pressure Drop	2323.650 Pa, 1048.838 Pa, 583.125 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	6.12%, 6.73%, 10.39%

Table A.39: Results for S1175 St14 14 14 14 case

A.40 Results for Sl175 St16 16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	1899.342 Pa
Overall Results	Total Heat Transfer	316.060 kW
Overall Results	Mean HTC (CFD)	219.878 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.393
Overall Results	Total Number of Tubes	599.0
Overall Results	Total Heat Transfer (Pipe) Area	9.409 m ²
Overall Results	Average Nu Deviation (Zu)	6.98%
Overall Results	Average Nu Deviation (HEDH)	12.56%
Overall Results	Average Nu Deviation (EDSU)	10.91%
Overall Results	Average dP Deviation	8.45%
Overall Results	HT/dP Ratio	166.40
Zone Results	Nu CFD	32.265, 31.062, 29.176, 26.376
Zone Results	Nu Zukauskas	30.013, 31.925, 31.762, 29.176
Zone Results	Nu HEDH	34.369, 35.252, 34.472, 31.728
Zone Results	Nu EDSU	32.512, 35.265, 34.393, 31.325
Zone Results	Deviation Zu	7.50%, 2.70%, 8.14%, 9.60%
Zone Results	Deviation HEDH	6.12%, 11.89%, 15.36%, 16.87%
Zone Results	Deviation EDSU	0.76%, 11.92%, 15.17%, 15.80%
Zone Results	Pressure Drop (Zukauskas)	932.764 Pa, 592.176 Pa, 369.774 Pa, 221.537 Pa
Zone Results	Pressure Drop	808.728 Pa, 532.237 Pa, 344.998 Pa, 213.378 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	13.30%, 10.12%, 6.70%, 3.68%

Table A.40: Results for Sl175 St16 16 16 16 case

A.41 Results for Sl175 St16 16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	2003.935 Pa
Overall Results	Total Heat Transfer	317.170 kW
Overall Results	Mean HTC (CFD)	221.370 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.791
Overall Results	Total Number of Tubes	601.0
Overall Results	Total Heat Transfer (Pipe) Area	9.440 m ²
Overall Results	Average Nu Deviation (Zu)	6.47%
Overall Results	Average Nu Deviation (HEDH)	12.15%
Overall Results	Average Nu Deviation (EDSU)	11.19%
Overall Results	Average dP Deviation	6.83%
Overall Results	HT/dP Ratio	158.27
Zone Results	Nu CFD	32.960, 29.657, 27.920
Zone Results	Nu Zukauskas	31.466, 31.847, 30.277
Zone Results	Nu HEDH	35.364, 34.616, 32.967
Zone Results	Nu EDSU	34.609, 34.555, 32.708
Zone Results	Deviation Zu	4.75%, 6.88%, 7.78%
Zone Results	Deviation HEDH	6.80%, 14.33%, 15.31%
Zone Results	Deviation EDSU	4.76%, 14.17%, 14.64%
Zone Results	Pressure Drop (Zukauskas)	1252.204 Pa, 594.928 Pa, 347.589 Pa
Zone Results	Pressure Drop	1110.976 Pa, 543.449 Pa, 349.510 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	11.28%, 8.65%, 0.55%

Table A.41: Results for Sl175 St16 16 16 16 case

A.42 Results for Sl175 St18 18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1370.994 Pa
Overall Results	Total Heat Transfer	301.091 kW
Overall Results	Mean HTC (CFD)	210.442 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	28.105
Overall Results	Total Number of Tubes	536.0
Overall Results	Total Heat Transfer (Pipe) Area	8.419 m ²
Overall Results	Average Nu Deviation (Zu)	6.46%
Overall Results	Average Nu Deviation (HEDH)	10.54%
Overall Results	Average Nu Deviation (EDSU)	8.76%
Overall Results	Average dP Deviation	16.43%
Overall Results	HT/dP Ratio	219.62
Zone Results	Nu CFD	30.104, 28.352, 27.212, 24.302
Zone Results	Nu Zukauskas	27.908, 28.595, 29.010, 27.279
Zone Results	Nu HEDH	31.498, 31.028, 30.995, 29.242
Zone Results	Nu EDSU	29.473, 30.548, 30.512, 28.558
Zone Results	Deviation Zu	7.87%, 0.85%, 6.20%, 10.92%
Zone Results	Deviation HEDH	4.43%, 8.62%, 12.20%, 16.90%
Zone Results	Deviation EDSU	2.14%, 7.19%, 10.81%, 14.90%
Zone Results	Pressure Drop (Zukauskas)	725.175 Pa, 430.627 Pa, 293.609 Pa, 188.115 Pa
Zone Results	Pressure Drop	606.417 Pa, 366.562 Pa, 241.128 Pa, 156.886 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	16.38%, 14.88%, 17.87%, 16.60%

Table A.42: Results for Sl175 St18 18 18 18 case

A.43 Results for Sl175 St18 18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1337.949 Pa
Overall Results	Total Heat Transfer	298.331 kW
Overall Results	Mean HTC (CFD)	209.013 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.787
Overall Results	Total Number of Tubes	525.0
Overall Results	Total Heat Transfer (Pipe) Area	8.247 m ²
Overall Results	Average Nu Deviation (Zu)	5.75%
Overall Results	Average Nu Deviation (HEDH)	9.88%
Overall Results	Average Nu Deviation (EDSU)	7.42%
Overall Results	Average dP Deviation	16.22%
Overall Results	HT/dP Ratio	222.98
Zone Results	Nu CFD	29.384, 27.623, 24.752
Zone Results	Nu Zukauskas	28.086, 28.390, 27.482
Zone Results	Nu HEDH	30.912, 30.370, 29.348
Zone Results	Nu EDSU	29.749, 29.816, 28.677
Zone Results	Deviation Zu	4.62%, 2.70%, 9.93%
Zone Results	Deviation HEDH	4.94%, 9.04%, 15.66%
Zone Results	Deviation EDSU	1.23%, 7.35%, 13.69%
Zone Results	Pressure Drop (Zukauskas)	855.950 Pa, 452.511 Pa, 270.481 Pa
Zone Results	Pressure Drop	732.974 Pa, 389.688 Pa, 215.286 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	14.37%, 13.88%, 20.41%

Table A.43: Results for Sl175 St18 18 18 18 case

A.44 Results for S1175 St23 18 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2156.427 Pa
Overall Results	Total Heat Transfer	316.963 kW
Overall Results	Mean HTC (CFD)	225.990 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.367
Overall Results	Total Number of Tubes	570.0
Overall Results	Total Heat Transfer (Pipe) Area	8.954 m ²
Overall Results	Average Nu Deviation (Zu)	2.73%
Overall Results	Average Nu Deviation (HEDH)	7.77%
Overall Results	Average Nu Deviation (EDSU)	7.77%
Overall Results	Average dP Deviation	21.10%
Overall Results	HT/dP Ratio	146.99
Zone Results	Nu CFD	26.192, 27.704, 36.029
Zone Results	Nu Zukauskas	25.362, 27.521, 37.628
Zone Results	Nu HEDH	26.904, 29.505, 42.159
Zone Results	Nu EDSU	25.396, 28.852, 42.992
Zone Results	Deviation Zu	3.27%, 0.67%, 4.25%
Zone Results	Deviation HEDH	2.65%, 6.11%, 14.54%
Zone Results	Deviation EDSU	3.14%, 3.98%, 16.20%
Zone Results	Pressure Drop (Zukauskas)	586.747 Pa, 471.833 Pa, 927.855 Pa
Zone Results	Pressure Drop	474.493 Pa, 428.815 Pa, 1253.119 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	19.13%, 9.12%, 35.06%

Table A.44: Results for S1175 St23 18 13 case

A.45 Results for S1175 St25 18 16 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	1746.978 Pa
Overall Results	Total Heat Transfer	314.216 kW
Overall Results	Mean HTC (CFD)	222.025 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	28.915
Overall Results	Total Number of Tubes	574.0
Overall Results	Total Heat Transfer (Pipe) Area	9.016 m ²
Overall Results	Average Nu Deviation (Zu)	4.27%
Overall Results	Average Nu Deviation (HEDH)	8.68%
Overall Results	Average Nu Deviation (EDSU)	9.19%
Overall Results	Average dP Deviation	15.62%
Overall Results	HT/dP Ratio	179.86
Zone Results	Nu CFD	25.747, 28.674, 29.100, 33.412
Zone Results	Nu Zukauskas	24.635, 27.719, 30.150, 35.412
Zone Results	Nu HEDH	26.497, 30.141, 32.829, 39.624
Zone Results	Nu EDSU	24.205, 29.560, 32.555, 40.152
Zone Results	Deviation Zu	4.52%, 3.44%, 3.48%, 5.65%
Zone Results	Deviation HEDH	2.83%, 4.87%, 11.36%, 15.68%
Zone Results	Deviation EDSU	6.37%, 3.00%, 10.61%, 16.79%
Zone Results	Pressure Drop (Zukauskas)	445.091 Pa, 454.552 Pa, 386.770 Pa, 516.841 Pa
Zone Results	Pressure Drop	341.970 Pa, 407.816 Pa, 362.551 Pa, 634.640 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	23.17%, 10.28%, 6.26%, 22.79%

Table A.45: Results for S1175 St25 18 16 13 case

A.46 Results for S1175 St27 2 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2055.921 Pa
Overall Results	Total Heat Transfer	311.889 kW
Overall Results	Mean HTC (CFD)	223.060 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	28.340
Overall Results	Total Number of Tubes	538.0
Overall Results	Total Heat Transfer (Pipe) Area	8.451 m ²
Overall Results	Average Nu Deviation (Zu)	2.21%
Overall Results	Average Nu Deviation (HEDH)	6.50%
Overall Results	Average Nu Deviation (EDSU)	6.74%
Overall Results	Average dP Deviation	21.98%
Overall Results	HT/dP Ratio	151.70
Zone Results	Nu CFD	24.715, 26.525, 35.965
Zone Results	Nu Zukauskas	24.393, 25.988, 37.168
Zone Results	Nu HEDH	25.279, 27.509, 41.667
Zone Results	Nu EDSU	23.641, 26.636, 42.441
Zone Results	Deviation Zu	1.32%, 2.07%, 3.24%
Zone Results	Deviation HEDH	2.23%, 3.58%, 13.68%
Zone Results	Deviation EDSU	4.54%, 0.42%, 15.26%
Zone Results	Pressure Drop (Zukauskas)	500.069 Pa, 409.960 Pa, 958.393 Pa
Zone Results	Pressure Drop	393.082 Pa, 370.215 Pa, 1292.624 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	21.39%, 9.69%, 34.87%

Table A.46: Results for S1175 St27 2 13 case

A.47 Results for S1175 St2 15 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2581.504 Pa
Overall Results	Total Heat Transfer	326.302 kW
Overall Results	Mean HTC (CFD)	234.767 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.624
Overall Results	Total Number of Tubes	626.0
Overall Results	Total Heat Transfer (Pipe) Area	9.833 m ²
Overall Results	Average Nu Deviation (Zu)	3.82%
Overall Results	Average Nu Deviation (HEDH)	9.85%
Overall Results	Average Nu Deviation (EDSU)	9.81%
Overall Results	Average dP Deviation	17.66%
Overall Results	HT/dP Ratio	126.40
Zone Results	Nu CFD	27.776, 32.424, 36.062
Zone Results	Nu Zukauskas	26.587, 32.647, 38.496
Zone Results	Nu HEDH	28.768, 35.944, 43.087
Zone Results	Nu EDSU	27.416, 36.037, 44.033
Zone Results	Deviation Zu	4.47%, 0.68%, 6.32%
Zone Results	Deviation HEDH	3.45%, 9.79%, 16.31%
Zone Results	Deviation EDSU	1.31%, 10.03%, 18.10%
Zone Results	Pressure Drop (Zukauskas)	703.331 Pa, 791.355 Pa, 875.798 Pa
Zone Results	Pressure Drop	591.373 Pa, 790.576 Pa, 1199.555 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	15.92%, 0.10%, 36.97%

Table A.47: Results for S1175 St2 15 13 case

A.48 Results for S1175 St2 17 14 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2176.806 Pa
Overall Results	Total Heat Transfer	323.794 kW
Overall Results	Mean HTC (CFD)	230.735 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.024
Overall Results	Total Number of Tubes	622.0
Overall Results	Total Heat Transfer (Pipe) Area	9.770 m ²
Overall Results	Average Nu Deviation (Zu)	4.93%
Overall Results	Average Nu Deviation (HEDH)	10.40%
Overall Results	Average Nu Deviation (EDSU)	10.82%
Overall Results	Average dP Deviation	14.01%
Overall Results	HT/dP Ratio	148.75
Zone Results	Nu CFD	28.222, 29.286, 34.199, 33.142
Zone Results	Nu Zukauskas	26.363, 28.952, 35.378, 36.100
Zone Results	Nu HEDH	29.252, 31.655, 39.181, 40.355
Zone Results	Nu EDSU	27.102, 31.246, 39.660, 40.971
Zone Results	Deviation Zu	7.05%, 1.15%, 3.33%, 8.19%
Zone Results	Deviation HEDH	3.52%, 7.48%, 12.72%, 17.87%
Zone Results	Deviation EDSU	4.13%, 6.27%, 13.77%, 19.11%
Zone Results	Pressure Drop (Zukauskas)	588.788 Pa, 483.405 Pa, 630.443 Pa, 495.986 Pa
Zone Results	Pressure Drop	477.239 Pa, 433.455 Pa, 663.148 Pa, 602.964 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	18.95%, 10.33%, 5.19%, 21.57%

Table A.48: Results for S1175 St2 17 14 13 case

A.49 Results for Sl175 St2 18 16 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	1633.883 Pa
Overall Results	Total Heat Transfer	313.926 kW
Overall Results	Mean HTC (CFD)	220.950 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.320
Overall Results	Total Number of Tubes	582.0
Overall Results	Total Heat Transfer (Pipe) Area	9.142 m ²
Overall Results	Average Nu Deviation (Zu)	5.04%
Overall Results	Average Nu Deviation (HEDH)	9.23%
Overall Results	Average Nu Deviation (EDSU)	8.93%
Overall Results	Average dP Deviation	12.13%
Overall Results	HT/dP Ratio	192.13
Zone Results	Nu CFD	28.242, 28.347, 29.800, 30.774
Zone Results	Nu Zukauskas	27.076, 28.925, 31.402, 33.723
Zone Results	Nu HEDH	29.256, 30.598, 33.270, 36.497
Zone Results	Nu EDSU	27.100, 30.060, 33.039, 36.641
Zone Results	Deviation Zu	4.31%, 2.00%, 5.10%, 8.74%
Zone Results	Deviation HEDH	3.47%, 7.36%, 10.43%, 15.68%
Zone Results	Deviation EDSU	4.21%, 5.70%, 9.80%, 16.01%
Zone Results	Pressure Drop (Zukauskas)	591.383 Pa, 439.839 Pa, 379.080 Pa, 374.391 Pa
Zone Results	Pressure Drop	476.846 Pa, 384.928 Pa, 357.027 Pa, 415.082 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	19.37%, 12.48%, 5.82%, 10.87%

Table A.49: Results for Sl175 St2 18 16 14 case

A.50 Results for Sl175 St2 2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	1118.178 Pa
Overall Results	Total Heat Transfer	284.839 kW
Overall Results	Mean HTC (CFD)	203.348 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	26.342
Overall Results	Total Number of Tubes	479.0
Overall Results	Total Heat Transfer (Pipe) Area	7.524 m ²
Overall Results	Average Nu Deviation (Zu)	5.08%
Overall Results	Average Nu Deviation (HEDH)	7.92%
Overall Results	Average Nu Deviation (EDSU)	6.17%
Overall Results	Average dP Deviation	15.12%
Overall Results	HT/dP Ratio	254.73
Zone Results	Nu CFD	28.405, 26.716, 25.024, 23.050
Zone Results	Nu Zukauskas	26.372, 26.822, 26.314, 24.874
Zone Results	Nu HEDH	29.261, 28.716, 27.642, 26.293
Zone Results	Nu EDSU	27.111, 27.976, 26.784, 25.287
Zone Results	Deviation Zu	7.71%, 0.39%, 4.90%, 7.33%
Zone Results	Deviation HEDH	2.92%, 6.97%, 9.47%, 12.33%
Zone Results	Deviation EDSU	4.77%, 4.51%, 6.57%, 8.85%
Zone Results	Pressure Drop (Zukauskas)	589.466 Pa, 365.564 Pa, 227.778 Pa, 148.630 Pa
Zone Results	Pressure Drop	477.443 Pa, 314.454 Pa, 201.066 Pa, 125.215 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	19.00%, 13.98%, 11.73%, 15.75%

Table A.50: Results for Sl175 St2 2 2 2 case

A.51 Results for S1175 St2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	1120.994 Pa
Overall Results	Total Heat Transfer	284.053 kW
Overall Results	Mean HTC (CFD)	204.508 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	26.427
Overall Results	Total Number of Tubes	472.0
Overall Results	Total Heat Transfer (Pipe) Area	7.414 m ²
Overall Results	Average Nu Deviation (Zu)	3.59%
Overall Results	Average Nu Deviation (HEDH)	6.57%
Overall Results	Average Nu Deviation (EDSU)	3.77%
Overall Results	Average dP Deviation	13.62%
Overall Results	HT/dP Ratio	253.39
Zone Results	Nu CFD	27.772, 26.160, 24.053
Zone Results	Nu Zukauskas	26.585, 26.638, 25.186
Zone Results	Nu HEDH	28.765, 28.144, 26.489
Zone Results	Nu EDSU	27.414, 27.341, 25.506
Zone Results	Deviation Zu	4.46%, 1.80%, 4.50%
Zone Results	Deviation HEDH	3.45%, 7.05%, 9.20%
Zone Results	Deviation EDSU	1.30%, 4.32%, 5.69%
Zone Results	Pressure Drop (Zukauskas)	703.875 Pa, 388.450 Pa, 213.979 Pa
Zone Results	Pressure Drop	589.741 Pa, 347.402 Pa, 183.851 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	16.22%, 10.57%, 14.08%

Table A.51: Results for S1175 St2 2 2 case

A.52 Results for S1175 St3 2 17 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	1535.853 Pa
Overall Results	Total Heat Transfer	306.407 kW
Overall Results	Mean HTC (CFD)	217.856 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.545
Overall Results	Total Number of Tubes	532.0
Overall Results	Total Heat Transfer (Pipe) Area	8.357 m ²
Overall Results	Average Nu Deviation (Zu)	2.72%
Overall Results	Average Nu Deviation (HEDH)	7.09%
Overall Results	Average Nu Deviation (EDSU)	7.66%
Overall Results	Average dP Deviation	19.86%
Overall Results	HT/dP Ratio	199.50
Zone Results	Nu CFD	23.670, 27.335, 27.527, 33.518
Zone Results	Nu Zukauskas	23.690, 25.998, 28.036, 34.869
Zone Results	Nu HEDH	24.452, 27.899, 30.248, 39.047
Zone Results	Nu EDSU	22.066, 27.068, 29.677, 39.505
Zone Results	Deviation Zu	0.08%, 5.14%, 1.81%, 3.87%
Zone Results	Deviation HEDH	3.20%, 2.02%, 8.99%, 14.16%
Zone Results	Deviation EDSU	7.27%, 0.99%, 7.24%, 15.15%
Zone Results	Pressure Drop (Zukauskas)	366.464 Pa, 390.330 Pa, 332.157 Pa, 535.901 Pa
Zone Results	Pressure Drop	232.936 Pa, 347.062 Pa, 300.317 Pa, 655.539 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	36.44%, 11.09%, 9.59%, 22.32%

Table A.52: Results for S1175 St3 2 17 13 case

A.53 Results for Sl2 St13 13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	8599.520 Pa
Overall Results	Total Heat Transfer	334.833 kW
Overall Results	Mean HTC (CFD)	263.903 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	38.358
Overall Results	Total Number of Tubes	640.0
Overall Results	Total Heat Transfer (Pipe) Area	10.053 m ²
Overall Results	Average Nu Deviation (Zu)	7.03%
Overall Results	Average Nu Deviation (HEDH)	17.97%
Overall Results	Average Nu Deviation (EDSU)	18.58%
Overall Results	Average dP Deviation	77.19%
Overall Results	HT/dP Ratio	38.94
Zone Results	Nu CFD	39.881, 38.901, 37.652, 34.461
Zone Results	Nu Zukauskas	38.918, 41.627, 41.885, 37.867
Zone Results	Nu HEDH	46.950, 47.555, 47.083, 42.333
Zone Results	Nu EDSU	44.839, 49.041, 48.510, 43.187
Zone Results	Deviation Zu	2.47%, 6.55%, 10.11%, 8.99%
Zone Results	Deviation HEDH	15.06%, 18.20%, 20.03%, 18.59%
Zone Results	Deviation EDSU	11.06%, 20.68%, 22.38%, 20.21%
Zone Results	Pressure Drop (Zukauskas)	2288.486 Pa, 1305.806 Pa, 874.034 Pa, 501.624 Pa
Zone Results	Pressure Drop	3897.949 Pa, 2238.427 Pa, 1459.837 Pa, 1003.306 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	70.33%, 71.42%, 67.02%, 100.01%

Table A.53: Results for Sl2 St13 13 13 13 case

A.54 Results for Sl2 St13 13 13 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	10090.631 Pa
Overall Results	Total Heat Transfer	335.620 kW
Overall Results	Mean HTC (CFD)	266.790 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	39.103
Overall Results	Total Number of Tubes	641.0
Overall Results	Total Heat Transfer (Pipe) Area	10.069 m ²
Overall Results	Average Nu Deviation (Zu)	6.78%
Overall Results	Average Nu Deviation (HEDH)	18.03%
Overall Results	Average Nu Deviation (EDSU)	19.40%
Overall Results	Average dP Deviation	72.72%
Overall Results	HT/dP Ratio	33.26
Zone Results	Nu CFD	41.204, 37.898, 35.820
Zone Results	Nu Zukauskas	42.010, 41.795, 39.405
Zone Results	Nu HEDH	49.031, 47.013, 44.085
Zone Results	Nu EDSU	48.932, 48.433, 45.150
Zone Results	Deviation Zu	1.92%, 9.33%, 9.10%
Zone Results	Deviation HEDH	15.96%, 19.39%, 18.75%
Zone Results	Deviation EDSU	15.79%, 21.75%, 20.66%
Zone Results	Pressure Drop (Zukauskas)	3449.644 Pa, 1435.031 Pa, 851.835 Pa
Zone Results	Pressure Drop	6277.442 Pa, 2335.992 Pa, 1477.197 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	81.97%, 62.78%, 73.41%

Table A.54: Results for Sl2 St13 13 13 13 case

A.55 Results for Sl2 St14 14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	4369.990 Pa
Overall Results	Total Heat Transfer	326.413 kW
Overall Results	Mean HTC (CFD)	247.274 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	34.782
Overall Results	Total Number of Tubes	600.0
Overall Results	Total Heat Transfer (Pipe) Area	9.425 m ²
Overall Results	Average Nu Deviation (Zu)	5.07%
Overall Results	Average Nu Deviation (HEDH)	14.39%
Overall Results	Average Nu Deviation (EDSU)	13.91%
Overall Results	Average dP Deviation	43.30%
Overall Results	HT/dP Ratio	74.69
Zone Results	Nu CFD	35.427, 35.442, 34.451, 31.813
Zone Results	Nu Zukauskas	33.705, 36.110, 36.766, 34.209
Zone Results	Nu HEDH	40.224, 40.891, 41.024, 38.010
Zone Results	Nu EDSU	37.854, 41.577, 41.725, 38.345
Zone Results	Deviation Zu	5.11%, 1.85%, 6.30%, 7.00%
Zone Results	Deviation HEDH	11.93%, 13.33%, 16.02%, 16.30%
Zone Results	Deviation EDSU	6.41%, 14.76%, 17.43%, 17.03%
Zone Results	Pressure Drop (Zukauskas)	1371.468 Pa, 830.939 Pa, 566.602 Pa, 338.431 Pa
Zone Results	Pressure Drop	1826.923 Pa, 1213.235 Pa, 831.872 Pa, 497.959 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	33.21%, 46.01%, 46.82%, 47.14%

Table A.55: Results for Sl2 St14 14 14 14 case

A.56 Results for Sl2 St14 14 14 14 case

Section	Key	Value
Overall Results	Total Pressure Drop	4736.400 Pa
Overall Results	Total Heat Transfer	325.947 kW
Overall Results	Mean HTC (CFD)	247.413 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	35.031
Overall Results	Total Number of Tubes	595.0
Overall Results	Total Heat Transfer (Pipe) Area	9.346 m ²
Overall Results	Average Nu Deviation (Zu)	4.41%
Overall Results	Average Nu Deviation (HEDH)	14.26%
Overall Results	Average Nu Deviation (EDSU)	14.44%
Overall Results	Average dP Deviation	37.10%
Overall Results	HT/dP Ratio	68.82
Zone Results	Nu CFD	36.513, 34.734, 31.745
Zone Results	Nu Zukauskas	35.975, 36.538, 34.060
Zone Results	Nu HEDH	41.548, 40.772, 37.727
Zone Results	Nu EDSU	40.843, 41.444, 38.029
Zone Results	Deviation Zu	1.49%, 4.94%, 6.80%
Zone Results	Deviation HEDH	12.12%, 14.81%, 15.85%
Zone Results	Deviation EDSU	10.60%, 16.19%, 16.52%
Zone Results	Pressure Drop (Zukauskas)	1957.990 Pa, 903.376 Pa, 477.057 Pa
Zone Results	Pressure Drop	2839.877 Pa, 1327.116 Pa, 569.408 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	45.04%, 46.91%, 19.36%

Table A.56: Results for Sl2 St14 14 14 14 case

A.57 Results for Sl2 St16 16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	1808.824 Pa
Overall Results	Total Heat Transfer	306.213 kW
Overall Results	Mean HTC (CFD)	224.535 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.265
Overall Results	Total Number of Tubes	525.0
Overall Results	Total Heat Transfer (Pipe) Area	8.247 m ²
Overall Results	Average Nu Deviation (Zu)	6.38%
Overall Results	Average Nu Deviation (HEDH)	11.69%
Overall Results	Average Nu Deviation (EDSU)	10.41%
Overall Results	Average dP Deviation	8.00%
Overall Results	HT/dP Ratio	169.29
Zone Results	Nu CFD	32.371, 30.643, 29.224, 26.644
Zone Results	Nu Zukauskas	29.283, 31.308, 31.038, 28.661
Zone Results	Nu HEDH	34.288, 34.920, 34.038, 31.269
Zone Results	Nu EDSU	31.696, 34.892, 33.906, 30.812
Zone Results	Deviation Zu	10.54%, 2.12%, 5.84%, 7.04%
Zone Results	Deviation HEDH	5.59%, 12.25%, 14.14%, 14.79%
Zone Results	Deviation EDSU	2.13%, 12.18%, 13.81%, 13.53%
Zone Results	Pressure Drop (Zukauskas)	809.907 Pa, 538.378 Pa, 338.310 Pa, 195.377 Pa
Zone Results	Pressure Drop	737.915 Pa, 513.402 Pa, 330.563 Pa, 226.944 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	8.89%, 4.64%, 2.29%, 16.16%

Table A.57: Results for Sl2 St16 16 16 16 case

A.58 Results for Sl2 St16 16 16 16 case

Section	Key	Value
Overall Results	Total Pressure Drop	1861.007 Pa
Overall Results	Total Heat Transfer	306.289 kW
Overall Results	Mean HTC (CFD)	225.389 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	30.488
Overall Results	Total Number of Tubes	522.0
Overall Results	Total Heat Transfer (Pipe) Area	8.200 m ²
Overall Results	Average Nu Deviation (Zu)	5.34%
Overall Results	Average Nu Deviation (HEDH)	11.24%
Overall Results	Average Nu Deviation (EDSU)	9.64%
Overall Results	Average dP Deviation	3.63%
Overall Results	HT/dP Ratio	164.58
Zone Results	Nu CFD	32.553, 29.501, 27.497
Zone Results	Nu Zukauskas	30.862, 30.743, 29.406
Zone Results	Nu HEDH	35.016, 33.665, 32.095
Zone Results	Nu EDSU	33.784, 33.490, 31.734
Zone Results	Deviation Zu	5.48%, 4.04%, 6.49%
Zone Results	Deviation HEDH	7.03%, 12.37%, 14.33%
Zone Results	Deviation EDSU	3.65%, 11.91%, 13.35%
Zone Results	Pressure Drop (Zukauskas)	1115.417 Pa, 527.676 Pa, 306.483 Pa
Zone Results	Pressure Drop	1046.577 Pa, 506.024 Pa, 308.406 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	6.17%, 4.10%, 0.63%

Table A.58: Results for Sl2 St16 16 16 16 case

A.59 Results for Sl2 St18 18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1275.920 Pa
Overall Results	Total Heat Transfer	288.953 kW
Overall Results	Mean HTC (CFD)	213.790 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.854
Overall Results	Total Number of Tubes	470.0
Overall Results	Total Heat Transfer (Pipe) Area	7.383 m ²
Overall Results	Average Nu Deviation (Zu)	5.83%
Overall Results	Average Nu Deviation (HEDH)	9.66%
Overall Results	Average Nu Deviation (EDSU)	8.57%
Overall Results	Average dP Deviation	10.31%
Overall Results	HT/dP Ratio	226.47
Zone Results	Nu CFD	30.237, 27.735, 26.846, 24.703
Zone Results	Nu Zukauskas	27.265, 28.093, 28.074, 26.492
Zone Results	Nu HEDH	31.461, 30.787, 30.330, 28.517
Zone Results	Nu EDSU	28.771, 30.280, 29.769, 27.751
Zone Results	Deviation Zu	10.90%, 1.27%, 4.38%, 6.75%
Zone Results	Deviation HEDH	3.89%, 9.91%, 11.49%, 13.37%
Zone Results	Deviation EDSU	5.09%, 8.40%, 9.82%, 10.98%
Zone Results	Pressure Drop (Zukauskas)	626.271 Pa, 389.174 Pa, 262.472 Pa, 161.906 Pa
Zone Results	Pressure Drop	536.723 Pa, 337.484 Pa, 234.770 Pa, 166.943 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	14.30%, 13.28%, 10.55%, 3.11%

Table A.59: Results for Sl2 St18 18 18 18 case

A.60 Results for Sl2 St18 18 18 18 case

Section	Key	Value
Overall Results	Total Pressure Drop	1226.883 Pa
Overall Results	Total Heat Transfer	284.676 kW
Overall Results	Mean HTC (CFD)	212.082 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.471
Overall Results	Total Number of Tubes	456.0
Overall Results	Total Heat Transfer (Pipe) Area	7.163 m ²
Overall Results	Average Nu Deviation (Zu)	5.06%
Overall Results	Average Nu Deviation (HEDH)	9.25%
Overall Results	Average Nu Deviation (EDSU)	6.19%
Overall Results	Average dP Deviation	13.47%
Overall Results	HT/dP Ratio	232.03
Zone Results	Nu CFD	29.220, 26.980, 24.573
Zone Results	Nu Zukauskas	27.672, 27.664, 26.460
Zone Results	Nu HEDH	30.740, 29.804, 28.351
Zone Results	Nu EDSU	29.178, 29.184, 27.567
Zone Results	Deviation Zu	5.59%, 2.47%, 7.13%
Zone Results	Deviation HEDH	4.94%, 9.47%, 13.33%
Zone Results	Deviation EDSU	0.15%, 7.55%, 10.86%
Zone Results	Pressure Drop (Zukauskas)	763.845 Pa, 408.892 Pa, 234.523 Pa
Zone Results	Pressure Drop	667.553 Pa, 364.630 Pa, 194.700 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	12.61%, 10.82%, 16.98%

Table A.60: Results for Sl2 St18 18 18 18 case

A.61 Results for Sl2 St23 18 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2338.716 Pa
Overall Results	Total Heat Transfer	303.666 kW
Overall Results	Mean HTC (CFD)	226.137 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	28.651
Overall Results	Total Number of Tubes	494.0
Overall Results	Total Heat Transfer (Pipe) Area	7.760 m ²
Overall Results	Average Nu Deviation (Zu)	3.94%
Overall Results	Average Nu Deviation (HEDH)	9.25%
Overall Results	Average Nu Deviation (EDSU)	9.58%
Overall Results	Average dP Deviation	36.65%
Overall Results	HT/dP Ratio	129.84
Zone Results	Nu CFD	26.108, 26.961, 34.239
Zone Results	Nu Zukauskas	25.065, 27.080, 36.901
Zone Results	Nu HEDH	26.831, 29.219, 41.408
Zone Results	Nu EDSU	24.989, 28.533, 42.150
Zone Results	Deviation Zu	4.16%, 0.44%, 7.21%
Zone Results	Deviation HEDH	2.70%, 7.73%, 17.31%
Zone Results	Deviation EDSU	4.47%, 5.51%, 18.77%
Zone Results	Pressure Drop (Zukauskas)	523.058 Pa, 434.948 Pa, 860.403 Pa
Zone Results	Pressure Drop	405.931 Pa, 396.054 Pa, 1536.731 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	22.39%, 8.94%, 78.61%

Table A.61: Results for Sl2 St23 18 13 case

A.62 Results for Sl2 St25 18 16 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2008.027 Pa
Overall Results	Total Heat Transfer	305.944 kW
Overall Results	Mean HTC (CFD)	227.310 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	29.045
Overall Results	Total Number of Tubes	510.0
Overall Results	Total Heat Transfer (Pipe) Area	8.011 m ²
Overall Results	Average Nu Deviation (Zu)	5.13%
Overall Results	Average Nu Deviation (HEDH)	8.92%
Overall Results	Average Nu Deviation (EDSU)	10.81%
Overall Results	Average dP Deviation	38.19%
Overall Results	HT/dP Ratio	152.36
Zone Results	Nu CFD	26.096, 28.227, 28.970, 33.270
Zone Results	Nu Zukauskas	24.068, 27.415, 29.889, 35.421
Zone Results	Nu HEDH	26.466, 30.095, 32.856, 39.725
Zone Results	Nu EDSU	23.628, 29.507, 32.585, 40.264
Zone Results	Deviation Zu	8.42%, 2.96%, 3.08%, 6.07%
Zone Results	Deviation HEDH	1.40%, 6.21%, 11.83%, 16.25%
Zone Results	Deviation EDSU	10.44%, 4.34%, 11.09%, 17.37%
Zone Results	Pressure Drop (Zukauskas)	380.026 Pa, 411.653 Pa, 367.336 Pa, 484.733 Pa
Zone Results	Pressure Drop	267.860 Pa, 367.217 Pa, 356.914 Pa, 1016.036 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	29.52%, 10.79%, 2.84%, 109.61%

Table A.62: Results for Sl2 St25 18 16 13 case

A.63 Results for Sl2 St27 2 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2265.775 Pa
Overall Results	Total Heat Transfer	297.994 kW
Overall Results	Mean HTC (CFD)	222.206 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.535
Overall Results	Total Number of Tubes	466.0
Overall Results	Total Heat Transfer (Pipe) Area	7.320 m ²
Overall Results	Average Nu Deviation (Zu)	1.62%
Overall Results	Average Nu Deviation (HEDH)	7.94%
Overall Results	Average Nu Deviation (EDSU)	7.80%
Overall Results	Average dP Deviation	43.66%
Overall Results	HT/dP Ratio	131.52
Zone Results	Nu CFD	24.399, 25.198, 35.017
Zone Results	Nu Zukauskas	24.127, 25.445, 36.008
Zone Results	Nu HEDH	25.230, 27.120, 40.452
Zone Results	Nu EDSU	23.282, 26.204, 41.078
Zone Results	Deviation Zu	1.13%, 0.97%, 2.75%
Zone Results	Deviation HEDH	3.29%, 7.09%, 13.43%
Zone Results	Deviation EDSU	4.80%, 3.84%, 14.76%
Zone Results	Pressure Drop (Zukauskas)	445.756 Pa, 370.249 Pa, 856.126 Pa
Zone Results	Pressure Drop	317.719 Pa, 323.825 Pa, 1624.231 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	28.72%, 12.54%, 89.72%

Table A.63: Results for Sl2 St27 2 13 case

A.64 Results for S12 St2 15 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2736.683 Pa
Overall Results	Total Heat Transfer	315.935 kW
Overall Results	Mean HTC (CFD)	236.664 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.074
Overall Results	Total Number of Tubes	543.0
Overall Results	Total Heat Transfer (Pipe) Area	8.529 m ²
Overall Results	Average Nu Deviation (Zu)	4.76%
Overall Results	Average Nu Deviation (HEDH)	10.44%
Overall Results	Average Nu Deviation (EDSU)	10.97%
Overall Results	Average dP Deviation	35.26%
Overall Results	HT/dP Ratio	115.44
Zone Results	Nu CFD	27.738, 31.628, 34.849
Zone Results	Nu Zukauskas	26.223, 32.019, 37.590
Zone Results	Nu HEDH	28.637, 35.482, 42.142
Zone Results	Nu EDSU	26.921, 35.520, 42.973
Zone Results	Deviation Zu	5.78%, 1.22%, 7.29%
Zone Results	Deviation HEDH	3.14%, 10.86%, 17.31%
Zone Results	Deviation EDSU	3.04%, 10.96%, 18.91%
Zone Results	Pressure Drop (Zukauskas)	626.191 Pa, 727.764 Pa, 790.562 Pa
Zone Results	Pressure Drop	519.857 Pa, 768.922 Pa, 1447.904 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	16.98%, 5.66%, 83.15%

Table A.64: Results for S12 St2 15 13 case

A.65 Results for S12 St2 17 14 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	2741.614 Pa
Overall Results	Total Heat Transfer	316.224 kW
Overall Results	Mean HTC (CFD)	235.975 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	31.051
Overall Results	Total Number of Tubes	550.0
Overall Results	Total Heat Transfer (Pipe) Area	8.639 m ²
Overall Results	Average Nu Deviation (Zu)	6.09%
Overall Results	Average Nu Deviation (HEDH)	10.68%
Overall Results	Average Nu Deviation (EDSU)	12.44%
Overall Results	Average dP Deviation	48.92%
Overall Results	HT/dP Ratio	115.34
Zone Results	Nu CFD	28.585, 28.917, 33.286, 33.589
Zone Results	Nu Zukauskas	25.744, 28.588, 35.142, 36.083
Zone Results	Nu HEDH	29.205, 31.558, 39.299, 40.430
Zone Results	Nu EDSU	26.443, 31.138, 39.791, 41.054
Zone Results	Deviation Zu	11.03%, 1.15%, 5.28%, 6.91%
Zone Results	Deviation HEDH	2.12%, 8.37%, 15.30%, 16.92%
Zone Results	Deviation EDSU	8.10%, 7.13%, 16.35%, 18.18%
Zone Results	Pressure Drop (Zukauskas)	505.090 Pa, 439.991 Pa, 611.876 Pa, 463.970 Pa
Zone Results	Pressure Drop	409.576 Pa, 402.671 Pa, 912.428 Pa, 1016.938 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	18.91%, 8.48%, 49.12%, 119.18%

Table A.65: Results for S12 St2 17 14 13 case

A.66 Results for Sl2 St2 2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	998.520 Pa
Overall Results	Total Heat Transfer	270.624 kW
Overall Results	Mean HTC (CFD)	205.708 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	26.039
Overall Results	Total Number of Tubes	420.0
Overall Results	Total Heat Transfer (Pipe) Area	6.597 m ²
Overall Results	Average Nu Deviation (Zu)	5.97%
Overall Results	Average Nu Deviation (HEDH)	8.25%
Overall Results	Average Nu Deviation (EDSU)	7.53%
Overall Results	Average dP Deviation	12.87%
Overall Results	HT/dP Ratio	271.03
Zone Results	Nu CFD	28.631, 26.266, 24.749, 22.738
Zone Results	Nu Zukauskas	25.762, 26.468, 25.934, 24.564
Zone Results	Nu HEDH	29.223, 28.612, 27.514, 26.045
Zone Results	Nu EDSU	26.462, 27.861, 26.642, 25.013
Zone Results	Deviation Zu	11.14%, 0.76%, 4.57%, 7.43%
Zone Results	Deviation HEDH	2.03%, 8.20%, 10.05%, 12.70%
Zone Results	Deviation EDSU	8.20%, 5.72%, 7.11%, 9.09%
Zone Results	Pressure Drop (Zukauskas)	506.326 Pa, 330.611 Pa, 211.645 Pa, 134.359 Pa
Zone Results	Pressure Drop	408.929 Pa, 276.413 Pa, 180.102 Pa, 133.077 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	19.24%, 16.39%, 14.90%, 0.95%

Table A.66: Results for Sl2 St2 2 2 2 case

A.67 Results for Sl2 St2 2 2 2 case

Section	Key	Value
Overall Results	Total Pressure Drop	992.556 Pa
Overall Results	Total Heat Transfer	267.755 kW
Overall Results	Mean HTC (CFD)	205.654 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	25.930
Overall Results	Total Number of Tubes	410.0
Overall Results	Total Heat Transfer (Pipe) Area	6.440 m ²
Overall Results	Average Nu Deviation (Zu)	4.64%
Overall Results	Average Nu Deviation (HEDH)	7.44%
Overall Results	Average Nu Deviation (EDSU)	5.08%
Overall Results	Average dP Deviation	15.04%
Overall Results	HT/dP Ratio	269.76
Zone Results	Nu CFD	27.704, 25.695, 22.821
Zone Results	Nu Zukauskas	26.229, 26.103, 24.469
Zone Results	Nu HEDH	28.642, 27.765, 25.809
Zone Results	Nu EDSU	26.926, 26.921, 24.752
Zone Results	Deviation Zu	5.63%, 1.56%, 6.73%
Zone Results	Deviation HEDH	3.27%, 7.46%, 11.58%
Zone Results	Deviation EDSU	2.89%, 4.55%, 7.80%
Zone Results	Pressure Drop (Zukauskas)	626.923 Pa, 353.482 Pa, 190.479 Pa
Zone Results	Pressure Drop	523.495 Pa, 309.207 Pa, 159.854 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	16.50%, 12.53%, 16.08%

Table A.67: Results for Sl2 St2 2 2 2 case

A.68 Results for Sl2 St3 2 17 13 case

Section	Key	Value
Overall Results	Total Pressure Drop	1825.120 Pa
Overall Results	Total Heat Transfer	297.471 kW
Overall Results	Mean HTC (CFD)	222.371 W/m ² K
Overall Results	Mean Nusselt Number (CFD)	27.641
Overall Results	Total Number of Tubes	475.0
Overall Results	Total Heat Transfer (Pipe) Area	7.461 m ²
Overall Results	Average Nu Deviation (Zu)	4.26%
Overall Results	Average Nu Deviation (HEDH)	7.47%
Overall Results	Average Nu Deviation (EDSU)	9.32%
Overall Results	Average dP Deviation	43.03%
Overall Results	HT/dP Ratio	162.99
Zone Results	Nu CFD	23.848, 27.199, 27.255, 32.968
Zone Results	Nu Zukauskas	22.950, 25.750, 27.762, 34.945
Zone Results	Nu HEDH	24.235, 27.894, 30.240, 39.220
Zone Results	Nu EDSU	21.348, 27.062, 29.668, 39.698
Zone Results	Deviation Zu	3.91%, 5.62%, 1.83%, 5.66%
Zone Results	Deviation HEDH	1.60%, 2.49%, 9.87%, 15.94%
Zone Results	Deviation EDSU	11.71%, 0.50%, 8.13%, 16.95%
Zone Results	Pressure Drop (Zukauskas)	304.072 Pa, 349.830 Pa, 311.437 Pa, 507.101 Pa
Zone Results	Pressure Drop	175.618 Pa, 305.758 Pa, 284.997 Pa, 1058.747 Pa
Zone Results	Deviation in Pressure Drop (Zukauskas)	42.24%, 12.60%, 8.49%, 108.78%

Table A.68: Results for Sl2 St3 2 17 13 case

Division of Fluid Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se



CHALMERS
UNIVERSITY OF TECHNOLOGY