Heat transfer rates in hot shell, cold tube inclined baffled small shell, and tube heat exchanger using CFD and experimental approach

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ABSTRACT

The work presented is an effort to realize the changes occurring for convective coefficients of heat transfer in STHX fitted with inclined baffles. Effort has been undertaken using Fluent, a commercially available CFD code on a CAD model of small STHX with inclined baffles with cold liquid flowing into the tubes and hot liquid flowing in the shell. Four sets of CFD analysis have been carried out. The hot liquid flow rate through shell compartments varied from 0.2 kg/sec to 0.8 kg/sec in steps of 0.2 kg/sec, while keeping the cold liquid flow condition in tube at 0.4 kg/sec constant. Heat transfer rates, compartment temperatures, and overall heat transfer coefficients, for cold liquid and hot liquid, were studied. The results given by the software using CFD approach were appreciable and comparatively in agreement with the results available by the experimental work, which was undertaken for the same set of inlet pressure conditions, liquid flow rates, and inlet temperatures of liquid for both hot and cold liquids. The experimental output results were also used to validate the results given by the CFD software. The results from the CFD analysis were further used to conclude the effect of baffle inclination on heat duty. The process thus followed also helped realize the effects of baffle inclination on convective heat transfer coefficient of the liquid flow through the shell in an inclined baffle shell and tube heat exchanger. The temperature plots for both cold and hot liquid were also generated for understanding the compartmental temperature distributions inclusive of the inlet and outlet compartments. The heat duty for a heat exchanger has been found to increase with the increase in baffle inclinations from zero degree to 20 degrees. Likewise, the convective heat transfer coefficients have also been found to increase with the increase in baffle inclinations.

Keywords: STHX-Shell and tube heat exchanger; CFD-Computational fluid dynamics.

NOMENCLATURE

Symbol	Specification	Dimension
do	Outer diameter of tube	0.015875m
di	Inner diameter of tube	0.01448m
ro	Outer radius of tube	0.0079m
ri	Inner radius of tube	0.00724m
PT	Tube pitch	0.02m
Lo	Total length of shell with tube end sheets	0.64m
L	Length of Flow	0.604m
Bt	Baffle thickness	0.0015m
Bs	Baffle spacing	0.086m
Ds	Inner diameter of shell	0.076m
Nb	Number of Baffles	06
N	Number of Tubes	08
Nc	Number of tube rows cross during shell flow	03
Np	Number of tube passes	01

INTRODUCTION

Fossil fuel has been the main source of energy for automotive traction and is widely used in the road transportation (Rojey and Alexandre, 2009). This is true both for light and heavy commercial goods transport at all levels. Automotive uses fossil fuel to run the internal combustion engine to generate power and continue to use them in near future. The exhaust from the automotive contains heat and is wasted, which also results in the addition of pollutants to air. If this exhaust waste is recovered by using a suitably modified heat exchanger (Bari and Hossain., 2013), this recovered heat may be used for producing electricity with thermoelectric generators or to preheat in turbo-charging principle (Copeland, Pesiridis, Martinez-Botas, Rajoo, Romagnoli & Mamat, 2014). This may improve the performance of the automotive worldwide. It may also alleviate the pollution problem to some extent. Hence, with this priority, the present work is envisaged on the development of an inclined baffle heat exchanger, as possible heat recovery equipment. STHX are easy to construct and effective heat transfer equipment. These are convenient to use and find their usage in various areas like industry, agriculture, automotive, and so on. These may be available in various sizes and configurations with change in number of tubes, tube bundles, baffle shapes, flow patterns, flow liquid, and so on (Kakac S, 1981). They are simple and easy to clean and assemble. The STHX have been considered for better heat transfer coefficients but have large shell side liquid pressure drops (Kern D Q, 1950). Thus, if it is possible to have a modified STHX, which has improved heat transfer coefficient and reduced pressure drop (Chillal and Kapale, 2018), then it may serve as equipment in automotive exhaust heat recovery. With this perspective, a

work is proposed to understand the effects of baffle inclinations on heat transfer rate variation. Gay et al. (1977) conducted experimental works on segmental baffle STHX and showed that the heat transfer coefficients for shell side decreased with the increase in baffle cut. Li et al. (1998) studied the effect of baffle spacing on shell side heat transfer rate in a segmental baffle STHX and found that the increase in baffle spacing led to an increase in the compartmental heat transfer rate due to increased fluid velocity through tube bundles. Clarke et al. (2000) studied the effect of fouling in a segmental baffle STHX using CFD technique. For this purpose, a commercial CFD code "FLUENT" was used. The study helped identify the potential regions of intense fouling in baffle compartments. Stevanovic et al. (2001) evaluated fouling in shell compartments of segmental baffle STHX using CFD technique. The author concluded the potential of the CFD technique used to study the heat transfer equipment. Son et al. (2001) undertook work to study the effects on shell side fluid flow with spiral baffles. CFX, a commercially available CFD code, was used. The work stated that heat transfer rates on shell side were better with spiral baffles as compared to segmental baffles. Zhang et al. (2009) studied the effect of overlapped helically shaped baffles on heat duty in STHX with continuous and discontinuous types of baffles. A CFD technique was adopted using 'Fluent', a commercially available CFD code, and it was found that the discontinuous type of helical baffles gave lesser heat transfer coefficients compared with continuous type of helical baffles. Ozden et al. (2010) studied the effect of baffle cut and baffle spacing on the heat duty on shell side using CFD approach. The study showed that the increase in number of baffles through tube packs improved the shell side heat transfer coefficients.

From the exhaustive literature survey carried out on STHX, it was found that not much work has been carried out on the design and development of STHX with inclined baffles. Further, the influence of inclined baffles on shell side heat transfer coefficients, heat duty for STHX with incline baffles as compared with segmental baffles, pressure drops of shell side fluid flow, and compartmental fluid flow patterns on shell side were not investigated in detail. Accordingly, the objectives of the present work involve the use of inclined baffle STHX with 10° and 20° baffle inclinations and evaluating the heat duty using CFD approach for a defined set of tube and shell fluid flow conditions. Further determination of heat duty for 0-degree segmental baffle STHX using CFD approach is done compared with the heat duties of 10-degree and 20-degree STHX considering the same set of shell/tube side fluid flow conditions. The study would help realize the influence of baffle inclination on heat duty for STHX. For this STHX, working models with 0°, 10°, and 20° inclined baffles were fabricated, and exhaustive experimental works were undertaken. Finally, experimental results were used to validate the results from CFD approach.

EXPERIMENTAL METHODOLOGY

A STHX with 750 mm length that may be accommodated in exhaust manifold was considered, and analysis was carried out both experimentally and using CFD approach. Two baffle inclinations of ten degree and twenty degrees were developed. Eight copper tubes were used to form tube bundle with a 45^0 triangular pitch. Six baffles were located with equal spacing with inclination mentioned along the shell flow direction. The material and properties used for the STHX with specifications are available in Appendix. The shell and the baffle plates were made up of steel. A hot shell-cold tube liquid flow condition was used in experimental and CFD analysis. Water was used as tube side cold liquid with constant flow rate of 0.4 kg/sec. Four liquid flow conditions were considered on shell with hot water of 0.2 kg/sec, 0.4 kg/sec, 0.6 kg/sec, and 0.8 kg/sec. The experimental setup was developed as described, and the study was conducted initially for the flow conditions mentioned. Later, the same input liquid flow conditions were used for CFD analysis. Sufficient time was allowed for the flow conditions to reach the steady state to have better approximate values of temperature, pressure, and discharge. The output parameters were tabulated, which were temperature and pressure. The same conditions as mentioned for experimental setup were used as inputs for the CFD analysis using 'Fluent', a commercially available CFD code. The outputs from the two approaches were compared. The reader is suggested to understand the meaning of inclined baffle going through figure 1. To assemble the tube bundle through baffle hole and alignment of baffle plates into the shell, sufficient care is taken during fabrication. The baffles were drilled with holes using plates in inclined position through the drilling spindle axis to ensure proper

positioning of the tube bundle through the baffle holes. The peripheral edge of the baffle plate was also generated by cutting the baffles in the inclined position of the plate to ensure proper mating of baffle edge with the shell inner circular surface.

Figure 1 shows the definition of baffle inclination. The baffle is inclined towards the shell side fluid flow direction by specified angle to define baffle inclination.
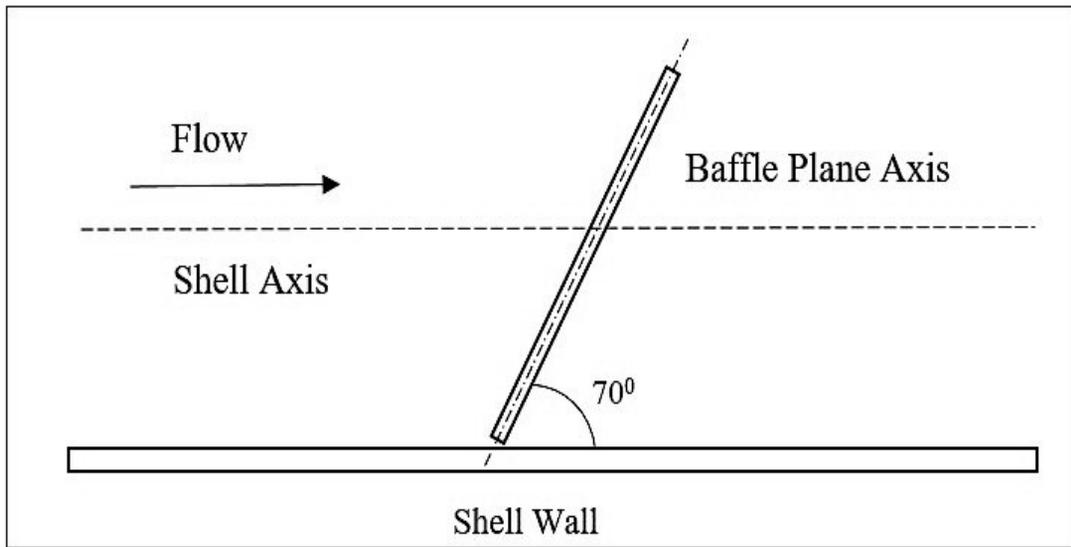
Figure 1. Representation for baffle angle.

Figure 2 shows the experimental setup used for Hot Shell Cold Tube Inclined Baffle STHX. The locations of fluid lines with temperature, pressure, and flow measuring instruments are clearly shown for both shell and tube side fluid flow.
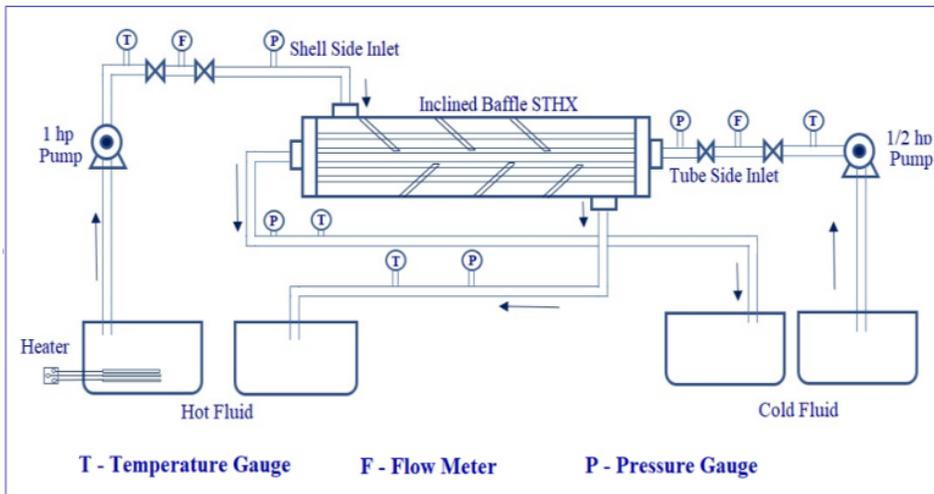
Figure 2. Experimental Setup for Hot Shell Cold Tube Inclined Baffle STHX.

CFD METHODOLOGY

The inlet flow rates and temperatures mentioned in experimentation were used for hot shell and cold tube inclined baffle heat exchanger solution by CFD approach using 'Fluent', a commercially available code. The number of iterations varied till the convergence conditions were achieved. The heat transfer rates for shell liquid and tube liquid were found to be equal for convergence. The material and both hot-cold liquid properties used for CFD analysis using 'Fluent' are given in Appendix. The material properties were taken from the data records, and the average fluid properties used for CFD analysis were found from the water properties tables for the appropriate temperatures used in experimental approach. The shell, tube end sheets, nozzles, and end covers were made up of carbon steel while, baffle plates with steel. The tubes were made up of copper. The results for 10^0 and 20^0 inclined baffle heat exchangers from numerical and experimental approach were compared for validation of CFD results. The results given by CFD/numerical approach validation are shown in graphs from figures 3 to 5 and tables 3 and 4, respectively. The results reasonably agree for temperature outputs in Kelvin found from numerical and experimental approach, and the variation is found to be less than 0.5 % as seen from table 3. Table 1 shows the details of the boundary conditions used in the CFD analysis by 'Fluent' software. The boundary conditions applied for both tube side fluid and shell side fluid and initial conditions defined are shown. The specifications of STHX used for both CAD modeling and fabrication of experimental models are detailed in nomenclature.

Table 1. Boundary Conditions Used in Conjugate Solution Using 'Fluent'.

Boundary Conditions		
Shell side	Tube Side	Initial conditions
Shell side Hot inlet Temperature input Mass velocity input	Tube side Cold inlet Temperature input Mass velocity input	Temperature Hot fluid temperature Cold fluid temperature Steel temperature
Shell side Hot outlet Temperature output Pressure output	Tube side Cold outlet Temperature input Mass velocity input	Tube wall Temperature = L-conjugate Outer Shell wall Heat flux =0

The material and their properties used in CFD work were the same, using which the experimental models were fabricated.

RESULTS AND DISCUSSION

It is mentioned in the experimental and CFD approach that two baffle angles of 10 and 20 degrees were used to evaluate temperatures output on shell and tube side liquid and heat duty of the heat exchanger. The tables 2, 3, and 4 below (page nos. 11 and 12) show the experimental results for the cases mentioned and their comparison with numerical/CFD approach for the same input temperatures and flow conditions. The experimental and numerical results thus found showed close agreement in temperature for both shell and tube side liquid and heat transfer outputs for the heat exchanger. Thus, numerical results were validated. Further, the results found by numerical approach for 0^0, 10^0, and 20^0 inclined baffle STHX for temperature and heat duty outputs are compared through graphs and used for stating concluding remarks. The temperatures were noted for shell and tube fluid at inlet and exit ports during

experimentation. The temperatures were observed for four sets of constant shell side fluid flow rates (0.2, 0.4, 0.6, and 0.8 kg/sec). The tube side cold fluid flow rate was kept constant at 0.4 kg/sec.

In table 3, the results for 10-degree inclined baffle STHX by CFD method are shown. These results are compared with experimental results for validation of numerical results.

In table 4, the results for 20-degree inclined baffle STHX by CFD method are shown. These results are compared with experimental results for validation of numerical results.

Figures 3, 4, and 5 show the temperature contours for different baffle inclinations with tube side constant flow rate of 0.4 kg/sec and varied shell side constant flow rates ranging from 0.2, 0.4, 0.6, and 0.8 kg/sec, respectively. Figure 3 shows the temperature contours for shell side fluid with 0-degree segmental baffles STHX for shell side flow rate of 0.6 kg/sec. These are plotted by the CFD software after satisfying convergence condition.
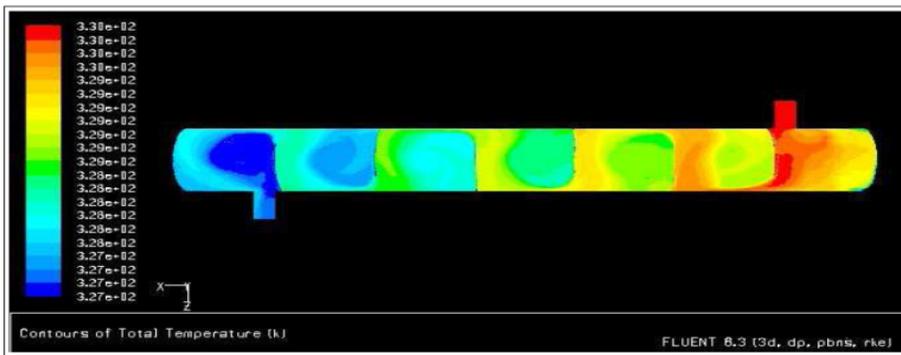
Figure 3. Temperature contours for 00 baffle for tube side constant flow rate of 0.4 kg/sec and shell side constant flow rate of 0.6 kg/sec.

Figure 4 shows the temperature contours for shell side fluid with 10-degree inclined baffles STHX for shell side flow rate of 0.6 kg/sec. These are plotted by the CFD software after satisfying convergence condition.
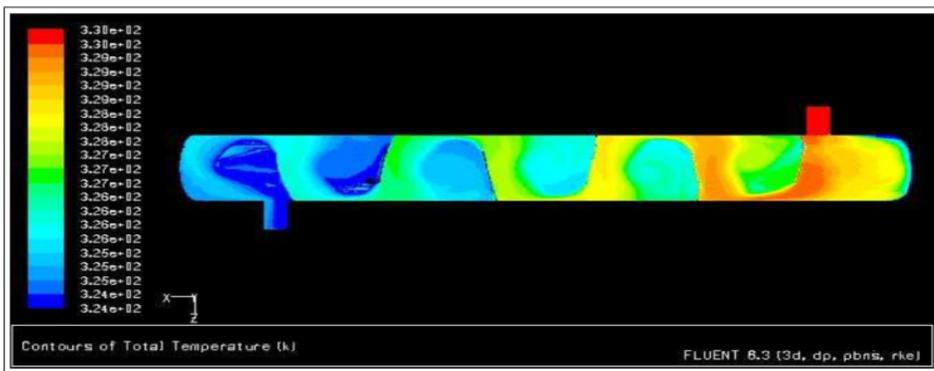
Figure 4. Temperature contours for 10^0 baffles for tube side constant flow rate of 0.4 kg/sec and shell side constant flow rate of 0.2 kg/sec.

Figure 5 shows the temperature contours for shell side fluid with 20-degree inclined baffles STHX for shell side flow rate of 0.6 kg/sec. These are plotted by the CFD software after satisfying convergence condition.
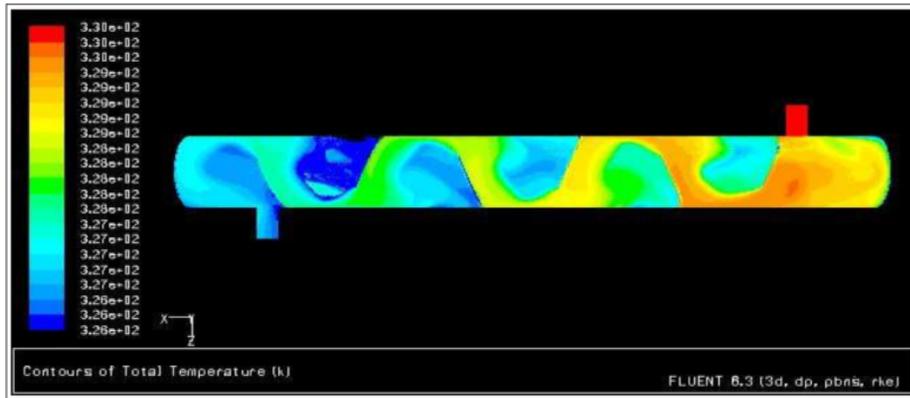
Figure 5. Temperature contours for 20^0 baffles for tube side constant flow rate of 0.4 kg/sec and shell side constant flow rate of 0.4 kg/sec.

Table 2. Experimental results for 10^0 and 20^0 inclined baffle STHX.

Shell flow in kg/sec	Temperature in K for 10^0 inclined baffle STHX				Temperature in K for 20^{0-} inclined baffle STHX			
	Tube in	Tube out	Shell in	Shell out	Tube in	Tube out	Shell in	Shell out
0.2	301.1	304.4	330.3	323.5	301.0	304.3	330.0	324.1
0.4	301.0	305.4	330.0	325.7	301.1	305.5	330.1	326.0
0.6	301.1	306.2	330.0	326.8	301.1	306.6	329.9	326.8
0.8	301.1	307.1	330.1	327.3	301.0	307.3	329.9	328.1

Table 3. Comparison of experimental and CFD results for 10^0 inclined baffle STHX.

Shell side Flow rate in kg/sec	Temperature in K				Heat Duty	
	Shell outlet		Tube outlet		Numerical	Experiment
	Numerical	Experiment	Numerical	Experiment		
0.2	324.52	323.5	303.64	304.4	4586	5605
0.4	326.5	325.7	304.4	305.4	5875	6598
0.6	327.4	326.8	304.8	306.2	6610	7408.5
0.8	328.1	327.3	305.5	307.1	7170	7736.4

Table 4. Comparison of experimental and CFD results for 20^0 inclined baffle STHX.

Shell side Flow rate in kg/sec	Temperature in ^{0}K				Heat Duty	
	Shell outlet		Tube outlet		Numeric al	Experime nt
	Numerical	Experiment	Numerical	Experiment		
0.2	324.6	324.1	303.6	304.3	4533	5651.8
0.4	326.6	326.0	304.3	305.5	5739	6638.3
0.6	327.4	326.8	304.8	306.6	6608	7309.6
0.8	328.0	328.1	305.4	307.3	7741	7804.6

Figure 6 and 7 show the shell side fluid exit temperature for all four sets of shell fluid flow rates for STHX with 100 baffle inclination. These are plotted for the temperature outputs obtained from experimental and numerical approach. Figures 8 to 9 show the shell side fluid exit temperature for all four sets of shell fluid flow rates for STHX with 20^0 baffle inclination.
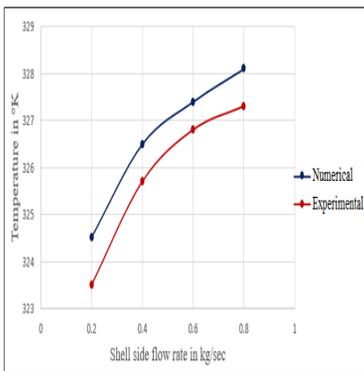
Figure 6. Shell exit temperature for 10^0 baffles STHX.
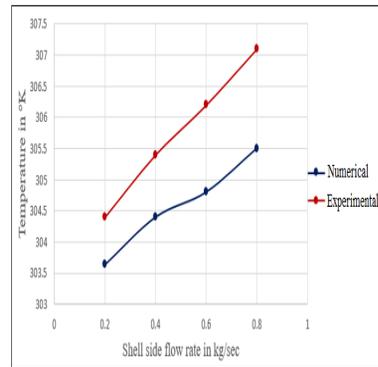
Figure 7. Tube exit temperature for 10^0 baffles STHX.
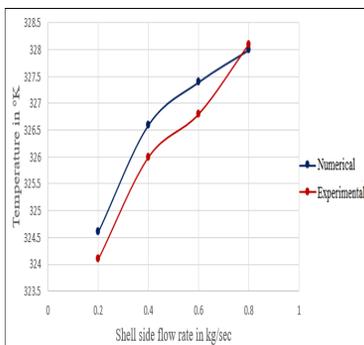
Figure 8. Shell exit temperature for 20^0 baffles STHX.
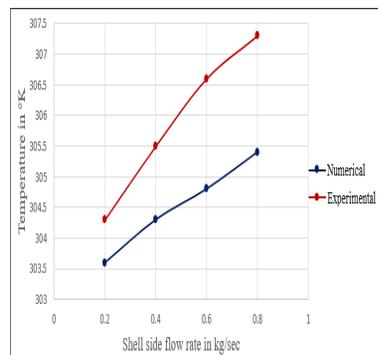
Figure 9. Tube exit temperature for 20^0 baffles STHX.

Figures 10 and 11 show heat duty and heat transfer coefficients, respectively, for all three baffle sets. The values for heat duty and heat transfer coefficients obtained by CFD are compared for all three baffle sets. The results from numerical analysis for three sets of baffles are plotted for heat transfer rates and overall heat transfer coefficients for heat exchanger against the varying shell side flow rates.
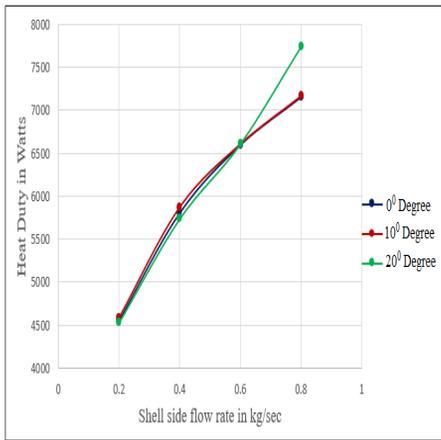
Figure 10. Heat duty for 0°, 10°, and 20° baffles STHX.
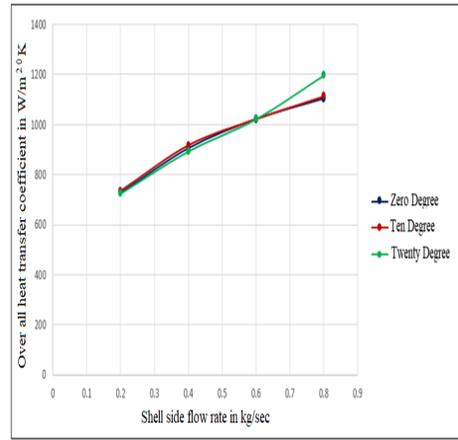
Figure 11. Heat Transfer Coefficients for 0°, 10°, and 20° baffle STHX.

Figures 12 and 13 show heat duty and heat transfer coefficients, respectively, for all three baffle sets in bar graph. The values for heat duty and heat transfer coefficients obtained by CFD are compared for all three baffle sets.
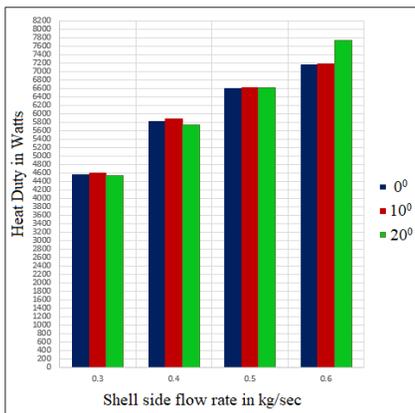
Figure 12. Heat duty for 0^0, 10^0, and 20^0 baffles STHX.
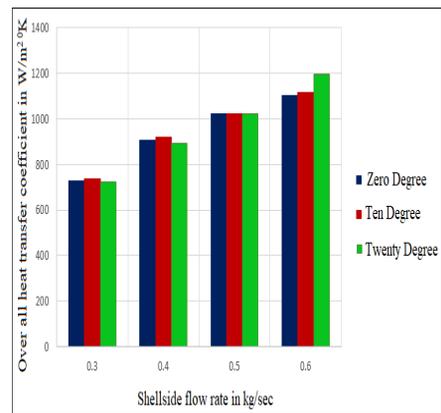
Figure 13. Heat Transfer Coefficients for 0^0, 10^0, and 20^0 baffles STHX.

FOR 10^0 INCLINED BAFFLE STHX

The water outlet temperature for shell side increases with the increase in water flow rate from 0.2 to 0.8 kg/sec and water outlet temperature in degree Celsius for numerical and experimental values match closely with up to 2% variation as seen in figure 6. The water outlet temperature on tube side flow increases with the increase in shell side water flow rate from 0.2 to 0.8 kg/sec and constant tube flow rate of 0.4 kg/sec. The tube outlet temperatures in degree Celsius for numerical and experimental values match closely with up to maximum 5% variations as seen in figure 7. The heat duty increases with the increase in shell side flow rate from 0.2 to 0.8 kg/sec, and the heat duty for experimental and numerical values is found to vary with maximum of 22% for lowest shell side liquid flow rate to minimum of 8% for highest shell side liquid fluid flow rate as seen in figures 10 and 12.

FOR 20^0 INCLINED BAFFLE STHX

The water outlet temperature for shell side increases with the increase in water flow rate from 0.2 to 0.8 kg/sec and water outlet temperature in degree Celsius for numerical and experimental values match closely with up to 1% variation as seen in figure 8. The water outlet temperature on tube side flow increases with the increase in shell side water flow rate from 0.2 to 0.8 kg/sec and constant tube flow rate of 0.4 kg/sec. The tube outlet temperatures in degree Celsius for numerical and experimental values match closely with up to maximum 5.5% variations as seen in figure 9.

The heat duty increases with the increase in shell side flow rate from 0.2 to 0.8 kg/sec, and the heat duty for experimental and numerical values is found to vary with maximum of 24% for lowest shell side liquid flow rate to minimum of 8% for highest shell side liquid fluid flowrate as seen in figures 10 and 12. The heat transfer coefficients were also found to be higher for heat exchanger with 20 degrees inclined baffle by 9% maximum when compared to zero degree segmental baffle heat exchanger.

CONCLUSION

STHX with 20^0 inclined baffle exhibits higher heat duty for higher shell side fluid flow rates. The heat duty has been enhanced by about 8% for STHX with 20^0 inclined baffles when compared with 0^0 segmental baffles STHX as seen from figures 10 and 12. The heat transfer coefficient is found to be highest for 20^0 inclined baffles STHX and is found to be for higher shell side water flow rates. The heat transfer coefficient for 20^0 inclined baffle STHX is about 9% higher when compared to 00 segmental baffle STHX as seen from figures 11and 13. Also, the coefficient of heat transfer for ten-degree baffle heat exchanger is higher by about 1% to 1.5% for when compared to zero-degree baffles at lower shell side fluid flow rates.

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APPENDIX

Table A. Properties of materials used in CFD analysis and Experimentation.

Copper:	Steel:
Density(ρ_{cu}) – 8978 Kg/m^3	Density(ρ_{st}) – 8030 Kg/m^3
Specific heat (C_{pcu}) – 381 J/kg ^{0}k	Specific heat (C_{pst}) – 502.5 J/kg ^{0}k
Conductivity (k_{cu}) – 387.6 W/m^{0}K	Conductivity (k_{st}) – 16.27 W/m^{0}K

Table B. Properties of hot and cold fluids used in CFD analysis and Experimentation.

Water Tube side:	Water shell side:
Density (ρ_t) – 996Kg/m^3	Density(ρ_s) – 990Kg/m^3
Specific heat (C_{pt}) – 4180 J/kg K	Specific heat (C_{ps}) – 4180 J/kg K
Conductivity (k_t) – 0.64 W/mK	Conductivity (k_s) – 0.63 W/mK
Viscosity (μ_t) – 0.00079 Kg/m-s	Viscosity (μ_s) – 0.00053 Kg/m-s