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THERMAL PERFORMANCE EVALUATION AND ANALYSIS OF THE EFFICIENT and SUSTAINABILITY SHELL AND TUBE HEAT EXCHANGER SYSTEM

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ABSTRACT
Shell and tube heat exchanger (STHE) is one of the most attractive heat exchanger types and widely used in many industrial processes, power generation, and chemical process industries because of the STHE suits the high-pressure applications and harsh environment. STHE porotype consists of a shell with a bundle of tubes and several baffles inside it. The objective of the study is to model and analysis of thermal performance and heat transfer in the advanced STHE system by using ANSYS Fluent along with the experiment. The advanced computational simulation tool, ANSYS Fluent, and AutoCAD were used to model the STHE system along with the one shell (8" diameter), five tubes (1" diameter) and four baffles. In this study, steel was selected for shell materials, copper and brass was compared to select better performance materials for tubes. The constructed STHE model has meshed and analyzed under two mediums (water and biogas) with different thermal conditions. Besides, the experiment results from the STHE prototype were used to investigate conversion efficiency and analyze heat transfer. The analysis of variance (ANOVA) method was used to analyze the significant effect of hot water flow rate and inlet temperature on heat transfer of the STHE prototype. Results from simulation and Karen's method indicated the heat release of the brass is lower than the copper in the system. Under various operating conditions, experimental results showed the conversion efficiency of the lab-scale STHE is a high range of 0.80-0.86. In addition, ANOVA results indicated that the hot water inlet temperature has a significant effect on heat transfer of STHE prototype.

Keywords: Shell and tube heat exchanger, heat transfer, conversion efficiency, ANOVA

1. INTRODUCTION
The Heat exchanger is an equipment, which used to transfer energy from a hot fluid to cold fluid while the fluid is passing through the heat exchanger, the temperature of fluid changes along the length of heat exchanger (Duan et al., 2016; Salahuddin et al., 2015). The shell and tube heat exchanger (STHE) consist of a shell (a large pressure vessel) with a bundle of tubes inside it. Heat exchangers are used in a wide variety of engineering applications, such as power generation, waste heat recovery, manufacturing industry, air-conditioning, refrigeration, space applications, and petrochemical industries (Duan et al., 2016). Large ratio of heat transfer area to volume is provided by the STHEs. Thus, STHE can be easily cleaned and has great flexibility to meet almost any service requirements. STHE can also be designed for high pressure relative to the environment and high-pressure difference between the fluid streams. In the previous studies, authors paid attention to analysing this problem both

experimentally and theoretically during design and development of shell and tube heat exchangers.

Kern's method presented the correction factor as a function of two variables R and S, which depends on the inlet and exit temperatures of the heat exchanger of both the fluids. Then, corrected effective mean temperature difference (CMTD) was calculated by multiplication of the correlation factor (F) and the logarithmic average of the temperature (LMTD) to evaluate the heat transfer performance (Nitsche and Gbadamosi, 2015). LMTD is used to calculate the heat transfer coefficient and critical to the heat transfer process because inlet fluid temperature affects both LMTD values and Reynold number (Singh, 2013). Surface area, correction factor, LMTD, and heat content are used to obtain the overall heat transfer coefficients and evaluate the performance of the STHE (EI-Said and Al-Sood, 2019). Water is utilized as a working fluid for both hot and cold streams and experiment results indicated that hybrid segmental baffle enhanced the energy efficiency by 1.27 to 1.4 times compared to conventional single segmental baffle. Recently, Kasmir and Joshi (2015) compared performance under the counter flow arrangement and parallel flow in the experimental study of STHE. Experiment results indicated that counter flow arrange gave better results that parallel flow while hot water supplied from boiler to the shell side and cold water came from main storage tank to tube side.

During the simulation studies, computational fluid dynamics (CFD) analysis of STHE has been widely performed to study temperature gradients, pressure distribution and velocity vectors. Ozden and Tari (2010) performed shell side CFD analysis of a small STHE to flow and temperature fields under a variable number of baffles and turbulent flow. In this study, water was used as medium inside the shell and simulation results showed 23% baffle cut gives slightly better results than the 25% and 36%. Singh and Kumar (2014) considered hot water is flowing inside the tube and cold water runs over the tube in the STEH model. It is concluded that the temperature of the experiment results and simulated values in CFD model are fair agreement and CFD can help to design and predict the heat performance of the STHE model. Ma (2012) conducted CFD and heat transfer simulation in a novel shell-tube type heat exchanger. The agreement between the predicted 3D flow structure in ANSYS model and particle image velocimetry (PIV) flow visualization results from experiment also verified that the CFD model is appropriated to study flow fields. Bogale (2014) conducted simulation for the heat transfer between the two fluids is analyzed using the concept of CFD in Gambit and Fluent software's. Simulation results indicated that redesigned STHE cam efficiently work to achieve required outlet temperature of 340°C to make beer for customer use. However, there is limited study to investigate the STHE performance by using biogas as a medium in the shell section.

The objective of this study is to understand the effect of operating factors, such as hot water inlet temperature and hot water flow rates on the system performance during the experimental in STHE porotype. Mixed level and ANOVA method were used to perform statistical analysis and analyze the system performance. Then, CFD simulation of the STHE model was performed to study the temperature and velocity distribution in the STHE. In this simulation, biogas and water were used as medium in the shell and tube to investigate the heat transfer between gas and water in the STHE. It is believed that the combination of experimental and simulation study will help to better understand and overall performance of STHE.

2. METHODOLOGY AND SCIENTIFIC APPROACHES

2.1 Effects of 4th IR on Education

As shown in Figure 1, the STHE prototype was designed and installed to analysis the temperature changes and heat transfer between one medium in shell and another medium in tube section. The principle of operation is simple that two fluids of different temperatures are brought into close contact, but they are not mixing with each other. One fluid runs through the tubes, and another fluid flows over the tubes (through the shell) to transfer heat between the two fluids. Temperature of two fluids will tend to equalize and the heat is simply exchanged from one fluid to the other and vice versa. Multiple pipes were used to connect between STHE, water pump, faucet, and water tank. The cold-water inlet was connected between faucet and STHE while cold water outlet was pointed to the water sink and STHE. For the cold water, inlet was connected between hot water tank and pump while outlet was connected between STHE and water sink. The inlet cold water connection is connected to the normal room temperature tap water and flow is control by the value and cold-water outlet is directly flow through the basin. The hot water inlet is taken in a large basin and water flow is controlled by another value. Three different hot water flow rates (e.g., 5.0 in3/s, 6.6 in3/s, and 8.2 in3/s) and four different hot water inlet temperatures (e.g., 95F, 105F, 115F, and 125 F) were selected and used to investigate the system performance of STHE under this experimental setup. Analysis of variance (ANOVA) method was used to identify the effect of hot water inlet temperature and flow rate on cold water outlet temperature and hot water outlet temperature while cold water inlet temperature of 66.8 F and cold water flow rates of X were kept.

Figure 1. Schematic Diagram and Experimental Setup of STHE Prototype

2.2 2D Design, 3D Modelling, and Simulation

Table 2 summarizes the detailed geometric dimensions of STHE system for the 2D design and 3D modeling. As shown in Figure 2, 2D design and 3D model of the STHE were designed using AutoCAD software and ANSYS software.

Table 1: Geometric Dimensions of STHE

Heat exchanger length, L	0.762 m
Shell inner diameter, D_i	0.2032 m
Tube Outer diameter, d_o	0.0254 m
Tube bundle geometry and pitch	0.0381 m
Number of the tube, N_t	5
Number of the baffle, N_b	4
Central baffle spacing, B	0.1016
Baffle inclination angle, θ	90 °θ

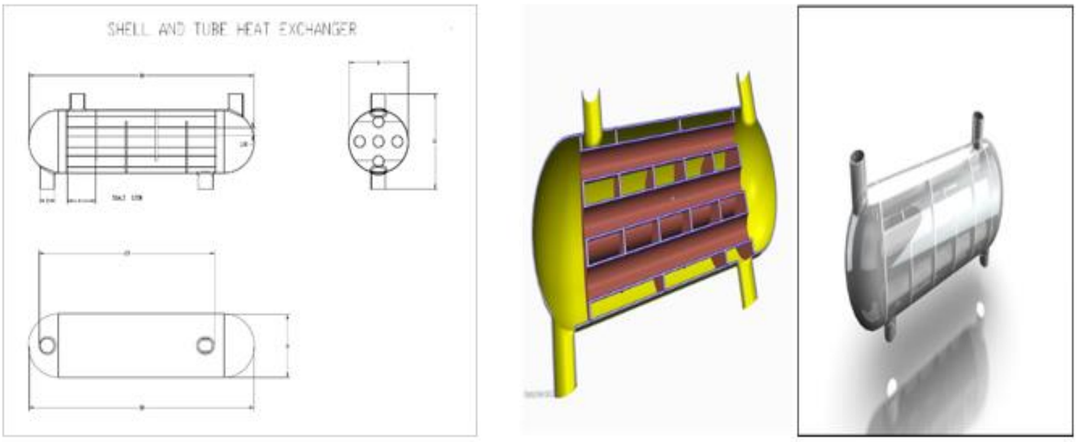

Figure 2: Schematic Diagram and Experimental Setup of STHE Prototype

Table 2: Thermal Properties of Materials and Medium in STHE Modelling and Simulation

Thermal Properties	Copper	Brass	Steel	Fresh Water	Biogas
Thermal Conductivity (W/(m°C)	140	125	45	0.604	0.026
Density (kg/m^3)	8940	8600	7872	997.4	1.2
Specific Heat (J/kg·°C)	385	62	481	4179	3493

Then, the 3D model is meshed by using the hexahedra mesh elements. Before meshing, fluid and the solid domain was created to have better control over the number of nodes. The simulation was carried out in the ANSYS® FLUENT® v18.1 software. During the simulation, absolute velocity formation, steady time, standard k-epsilon turbulence model, standard wall function and pressure-based solver were used. Water and biogas were selected as the medium for the copper tubes and shell section. Inlet velocity of biogas and water are 10 m/s and 2 m/s while the inlet temperature of biogas and water are 726.85°C and 26.85°C, respectively. Each shadow wall should be select in boundary condition and have to make couple with the wall thickness of 0.03 m. Together with the continuity and momentum equations, the two equation of k-ε model will be solved with the SIMPLE algorithm. Solution initialization was standard method and solution was initializing from inlet with 26.85°C. Under the above boundary conditions and solution initialize condition, the simulation was set for 300 iterations and Navier-Stokes Equations were to analyse the temperature and velocity distribution in the STHE prototype.

3. RESULTS AND DISCUSSION

Table 4 represents the inlet/outlet temperature, volume, mass flow rate of the hot water and cold water during the experiment in the STHE prototype. Then, temperature differences, mass flow rate and specific heat were used to calculate the heat in and heat out for hot water and cold water. The overall efficiency was calculated by diving the heat out and heat in. Results indicated that the conversion efficiency of STHE system is a range of between 80% to 86%. Thus, the STHE prototype has good conversion efficiency and can be used to capture residual heat for the combustion process.

Table 3: Thermal Properties of Materials and Medium in STHE Modelling and Simulation

Hot Water				Cold Water						
Temp In (°C)	Temp Out (°C)	Volume (L)	Mass Flow Rate (kg/sec)	Temp In (°C)	Temp Out (°C)	Volume (L)	Mass Flow Rate (kg/sec)	Heat In (kW)	Heat Out (kW)	Eff.
34.8	31.61	18.2	0.182	13.16	20.11	7.2	0.072	2.450	2.090	0.85
37	33.5	17.4	0.174	13	18.88	8.3	0.083	2.551	2.052	0.80
40.05	34.77	20.6	0.206	15.61	24.51	10.2	0.102	4.549	3.80	0.84
43.94	39.27	22.0	0.220	13	24.61	7.6	0.076	4.288	3.679	0.86
8.88	5.55	23.8	0.238	-10.6	-3.24	8.7	0.087	3.322	2.711	0.82
53	46.77	22.7	0.227	15.61	27.94	9.5	0.095	5.915	4.885	0.83

As shown in Table 4, cold water inlet temperature and flow rate was set as constant of 19.3°C and 0.16 L/s during the test. Mixed level factorial design method was applied to identify the effect of hot water inlet temperature and flow rate on the cold water and hot water outlet temperatures in STHE prototype. There are 3 individual levels for the hot water flow rate while 4 individual levels for hot water inlet temperature. There are 3 replications for each test run. Average temperatures were collected for each condition in the last column of cold water outlet temperature and hot water outlet temperature. Mixed level method and ANOVA test were used to analyse the differences among the group mean under different operating condition (Qian et al., 2014; Qian et al., 2018). Table 5 summarizes the ANOVA results, include a degree of freedom (DF), adjusted sum of squares (Adj SS), adjusted mean square (Adj MS), F-value and P-value. From the ANOVA table, results indicated that the hot water inlet temperature has a significant effect on the cold water outlet temperature because the P-value is smaller than 0.05.

Table 4: Summary of Hot and Cold Water Outlet Temperatures at Variable Operating Conditions

Hot Water Flow Rate	Hot Water Inlet Temp. (°C)	Cold Water Outlet Temp. (°C)				Hot Water Outlet Temp. (°C)			
(L/min)	(°C)	#1	#2	#3	Avg.	#1	#2	#3	Avg.
5	35.00	21.11	21.17	21.28	21.17	30.17	30.11	30.22	30.17
5	40.56	24.89	24.67	24.89	24.83	29.72	29.56	29.72	29.67
5	46.11	27.28	27.33	27.28	27.28	29.00	28.89	29.06	29.00
5	51.67	29.17	28.89	29.06	29.06	35.72	35.78	35.83	35.78
6.6	35.00	22.89	22.94	23.00	22.94	34.67	34.56	34.50	34.56
6.6	40.56	25.06	25.11	25.06	25.06	34.17	34.11	34.22	34.17
6.6	46.11	28.17	28.06	28.00	28.06	38.50	38.56	38.61	38.56
6.6	51.67	29.39	29.50	29.33	29.39	38.06	37.94	38.00	38.00
8.2	35.00	23.06	23.17	23.22	23.17	37.00	36.94	36.89	36.94
8.2	40.56	25.78	25.56	25.67	25.67	40.22	40.33	40.22	40.28
8.2	46.11	27.61	27.28	27.22	27.39	39.61	39.56	39.67	39.61
8.2	51.67	28.61	29.00	29.06	28.89	39.17	38.89	39.06	39.06

Table 5: Summary of ANOVA Results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	253.293	50.6587	52.11	0.000
Hot Water Inlet Flow Rate	2	4.727	2.3633	2.43	0.169
Hot Water Inlet Temperature	3	248.567	82.8556	85.22	0.000
Error	6	5.833	0.9722		
Total	11	29.127			

Contour plot represented cold-water outlet temperature change as response variable from two predictor variables, hot water inlet temperature on x-axis and hot water flow rate on y-axis. In this contour plot, cold water inlet temperature = 19.3°C, cold water inlet flow rate = 0.16 L/s, and hot water inlet flow rate = 0.11 L/s. Results indicated that if the desired cold water temperature in the STHE prototype is above 26.7 °C (80 °F), the hot water inlet temperature should be at least 44.3 °C (110 °F).

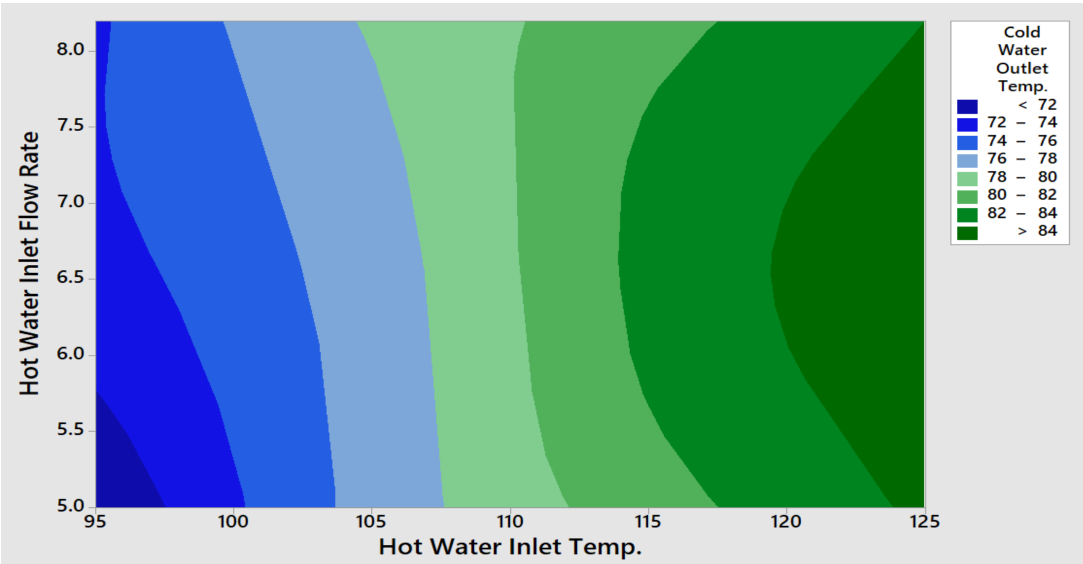

Figure 3. Contour Plot of Cold-Water Outlet Vs Hot Water Inlet Temp and Flow Rate

Figure 4 illustrates the temperature distribution in the STHE model. In this simulation, cold water was passed through the tube side and hot biogas was passed through the shell side. The initial temperature of water in tube side is assumed to be 22 °C and biogas temperature is set at 150 °C. As shown in Figure 4, the temperature of cold water is increased from 26 °C (299.1 K) to 658°C (931.1 K) in the tube section and the heat is transferred from biogas to the cold water. The temperature contours plot across the cross section of the baffle along the length of heat exchanger provided an idea of the flow direction. It was found that cold water was transported from upper right of tube to the bottom left of tube side while the hot biogas was entered from the upper right and exited from down left in the STHE prototype.

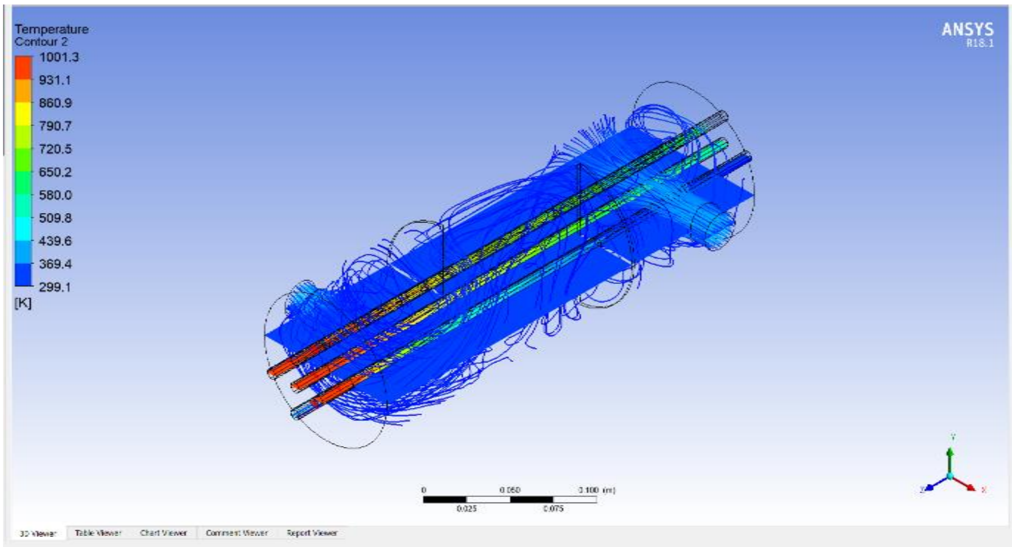

Figure 4. Variation of Temperature in the STHE Model

As shown in Figures 5 and 6, the transient thermal models were used to analyze and compare the heat transfer between the tubes and shell. Stainless steel was used as shell material while heat transfer was compared between the copper tube and brass tube. Engineering data of materials (copper, brass and stainless steel) and fluids (biogas, water) were created by using ANSYS thermal analysis. Results indicated that the copper has a higher temperature around the tubes and better heat transfer than the brass tube. This study also indicated that the possibility of using biogas as a heat source to provide hot water for space heating in residential and commercial buildings.

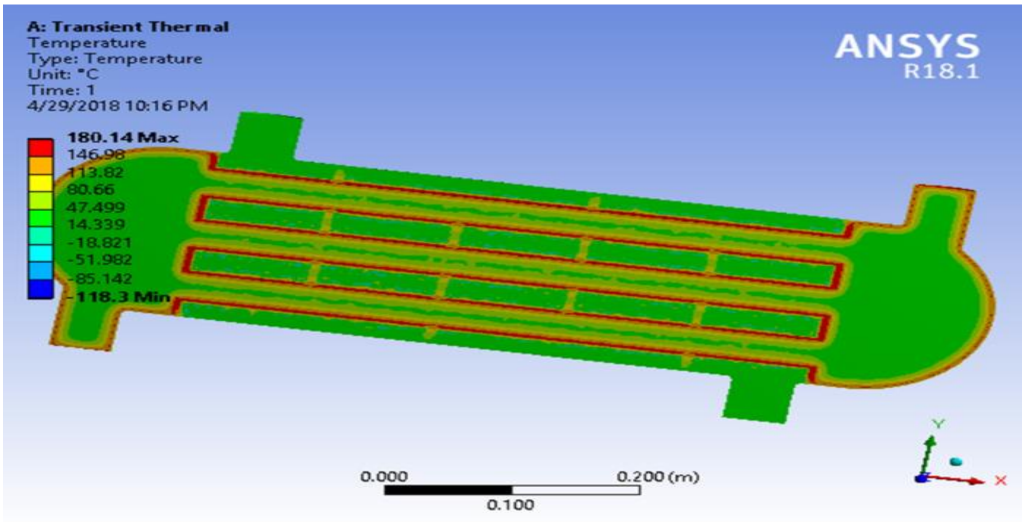

Figure 5. Thermal Analysis of STHE Model with Copper Tubes

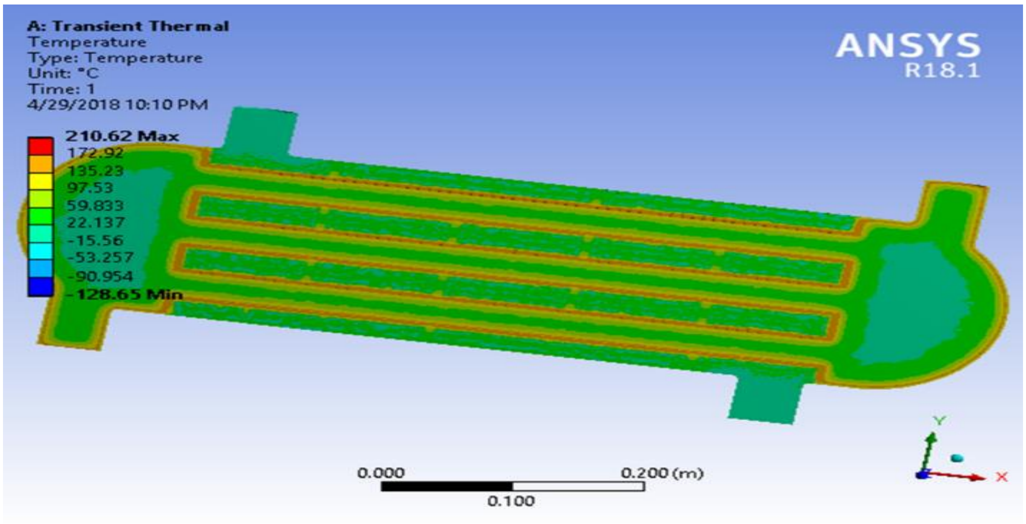

Figure 6. Thermal Analysis of STHE Model with Brass Tubes

3.1 Document Search

bibliometric study further considered specific parameters, namely subject topic and document types. The results were limited to the Computer Science, Education science, Social Science, Environmental and Engineering subjects, and although the documents in the research results were limited to the Final peer-review conference processing and journal articles published in English only, there was no restriction on the date of publication of the documents. As the next step, it was feasible to combine the results from the two databases (Scopus 301 documents and Web of Science 427 documents). After re-evaluating the alignment of the titles and keywords of the resultant 728 documents to the research theme, 146 articles were excluded, leaving the authors with a portfolio of 582 relevant articles.

4. CONCLUSIONS

System performance of the shell and tube heat exchanger was evaluated by both experimental and computational method. The modelling and meshing of STHE were done by using the ANSYS Fluent software. Results indicated that various operating conditions have a significant effect on the performance of the lab-scale STHE. It was found that the STHE prototype has good conversion efficiency is a high range of 0.80-0.86. In addition, ANOVA results indicated that the hot water inlet temperature has a significant effect on heat transfer of STHE prototype. CFD simulation and analysis results showed copper tube has a better heat transfer than brass tube to transfer the heat from biogas into water. These results confirmed that the STHE with copper tubes are very effective tube material in STHE model. Experimental and simulation study will help us to develop new heat exchanger system that can capture the residual from hot flue gas and provide hot water for residential and commercial buildings.

4.1 Future Studies

Future scope from my study is that different baffle angle can be used in the STHE exchanger so as to increase more heat transfer inside the heat exchanger. This work can be extended by using same working fluid for heat exchanger. Analysis can be done in ANSYS workbench by varying the baffle angle and change the flow position for a given heat exchanger.

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