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Design and analysis of waste heat recovery heat exchanger boiler

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Abstract

A waste heat recovery heat exchanger boiler is an energy recovery heat exchanger that recovers heat from a hot gas stream. The waste heat recovery heat exchanger boiler is a vertical type, in which the heat is to be recovered from hot sulfur dioxide gas at 300˚C; that enters in to horizontal tubes at 200 kg/hr. Such 16 tubes are placed in staggered arrangement. Accordingly to achieve desired generation of steam, electrical heating location are employed with the help of 21 coils. However the current problems in system are: 1) Very small steam generation 2) over heating of electric coils. The investigation aims to suggest remedies to overcome these problem. An experimental work is performed, followed by in -depth numerical investigation of waste heat recovery heat exchanger boiler. It is expected that heat transfer rate and there by steam generation will be enhanced.

Keywords:*Waste heat recovery heat exchanger boiler, shell and tube heat exchanger, electric coil, Numerical analysis, heat transfer coefficient and steam rate.*

1. Introduction

Heat recovery heat exchanger boilers, also known as waste heat recovery heat exchanger boilers or heat recovery steam generators (HRSGs), form an inevitable part of chemical plants, refineries, power plants, and process systems. They are classified in several ways, as can be seen in according to the application, the type of heat exchanger boiler used, whether the flue gas is used for process or mainly for heat recovery, cleanliness of the gas, and configuration of boiler , to mention a few. The main classification is based on whether the heat exchanger boiler is used for process purposes or for energy recovery. Process waste heat recovery heat exchanger boilers are used to cool waste gas streams from a given inlet temperature to a desired exit temperature for further processing purposes. An example can be found in the sugar factory where the sulfur dioxide gas stream is cooled to a particular gas temperature and then taken to out for further processing. The exit gas temperature from the heat exchanger boiler is an important parameter affecting the downstream process reactions and hence is controlled by using a gas bypass system. Steam generation is of secondary importance in such plants.

In heat recovery applications, the gas is cooled as much as possible while avoiding low temperature corrosion. Examples can be found in gas turbine exhaust waste heat recovery. Recovery from incinerators, furnaces, and kilns. The objective here is to maximize energy recovery. If the gas stream is clean, water tube boilers with extended surfaces can be used. In solid or liquid waste incineration applications, the gas is generally has contamination and may contain corrosive compounds, acid vapors, ash, and particulates. If the ash contains compounds of sodium, potassium, or nonferrous metals, slagging is effects on heat transfer surfaces if these compounds become molten. In these cases, bare tube boilers there is provision of cleaning the tubes with soot blowers or a rapping mechanism are usually used. A water-cooled furnace, which cools the gas stream to a temperature below the ash melting temperature and hence minimizes slagging on the convective surfaces, may also be necessary. Raw sulfur is burned with in a combustion chamber, to give sulfur dioxide, oxygen, and nitrogen gases. The gases, at about 500-600 F pass through a heat exchanger boiler generating saturated or superheated steam.

Heat exchangers play an important role in product quality, energy utilization, and systemic economy efficiency. In many types of heat exchangers, the tubes are arranged as a bundle or a bank in an in-line or staggered manner. Typically, one fluid flows over the tube banks, while the other fluid with a different temperature passes through the tubes. With the fluid outside tubes flowing cross over tube bundle or bank, the transverse velocity component of fluid that impinging on tubes vertically is augmented greatly. A non-uniformity of the flow distribution accompanying the secondary flow comes, which enhances the turbulence and augments the heat transfer on the tube surfaces, and the characteristics is very different from that of fluid flowing parallel to tubes. The heat transfer characteristics for tube banks in cross flow are of important practical interest, which also represents an idealization of many other industrially important processes, such as flow in filtration, biological systems and fibrous media as encountered in polymer processing and in insulation materials. Therefore, it is of importance to study characteristics of fluid flow and heat transfer for tube banks in cross flow, which would contribute to predict the heat transfer and to design or develop heat exchanger appropriately. The convective heat transfer characteristics for tube bundles or banks in cross flow have been developed over the ranges of geometric characteristics covering many practical needs. Study on the heat transfer characteristics of cross flow over tube banks has been extensively conducted from the early of 20th century.

Colburnproposed a correlation of heat transfer for flow across tube banks with staggered tubes

2. Literature Review

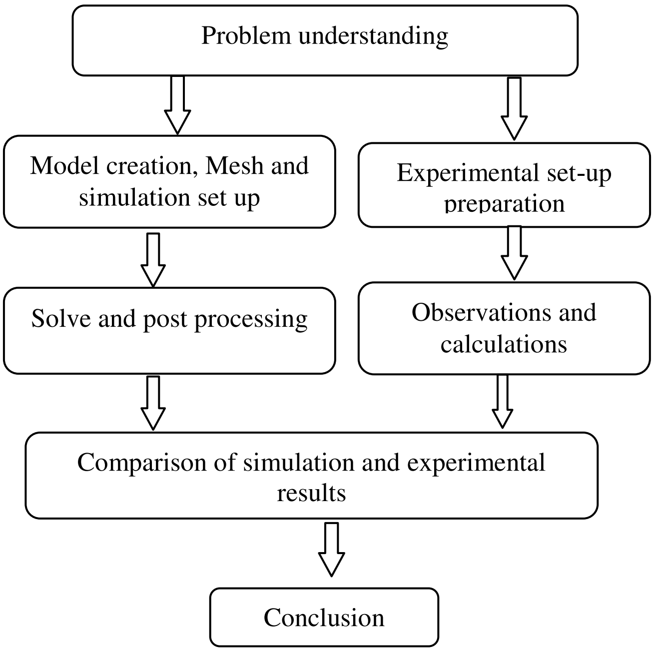
Sheng Shang et al. [1]Recovering heat from the flue gas of a gas-fired boiler can both improve boiler efficiency and decreasepollutant emissions. To improve the efficiency of the gas-fired boiler in a more cost effective and higher efficient way, a non-contact total heat recovery (NCHR) system is proposed for recovering heat from flue gas for use in heating and humidifying the oxidizing air of the boiler. Using the NCHR system, boiler efficiency can be promoted to 103.4% for an oxidizing air temperature of 0°C. Boiler efficiency increases with increasing inlet oxidizing air temperature and relative humidity. The energy saving potential for a year when running the NCHR system is 12.97% higher compared to a traditional boiler. For a system running continuously, the payback period of the NCHR system is one year relative to the traditional boiler and three years relative to the condensing boiler.
O. M. Al-Rabghi et al. [2] The literature givesreview of waste heat recovery and utilization is presented. The potential for re-using theotherwise wasted heat in different branches of industry is discussedconcluded that there exist numerous opportunities for recuperating and using waste heat. There is considerable potential exists for recovering some of the wasted energy in industrial processes, and of using it to improve plant performance. Research and development efforts seem to be focused especially on heat exchangers that utilize heat pipes, Rankine cycle and heat pumps.
Arafat A. Bhuiyan et al.[3]Different experimental and numericalstudies performed are reviewed, grouped and summarized based on the types of heat exchangers, heat transfer and pressure drop performance, effects of geometrical parameters under different flow conditions. This highlights on the existing technologies and emerging trends in designing of finned-tube heat exchangers considering different arrangements and geometric parameters under variable flow conditions which will be helpful for selecting appropriate design depending on the requirement. Wavy fin show larger heat transfer performance. Pressure drop is also significant as compared to plain fin. The effects of longitudinal pitch (Ll) on the heat transfer and the pressure drop characteristics are significant. S as the flow becomes free and less compact with the increase in the tube pitch. As the pressure drop decrease is more significant than heat transfer, so the efficiency goes high with the increase in tube pitch. As the fin pitch decrease, the flow becomes more streamlined. It affects the heat transfer performance as well as pressure drop characteristics.
M. Ishak et al. [4]The objectives of this article are to provide an overview of the published works that are relevant to the tube banks heat exchangers. Overview of available data says that the heat transfer and pressure drop characteristics of the heat exchanger rely on many parameters. Such parameters as follows: external fluid velocity, tube configuration (in-line/staggered, series), tubes rows, tube spacing, fin spacing, shape of tubes, etc. Studies show that the heat transfer coefficient and pressure drop increase with increased external velocity of fluid. The heat transfer coefficient and pressure drop increase with increased fin density.
Lin Liu et al. [5] The experiments were conducted in heat transfer test system with hot air in the tube side and cold air in the shell side. Overall heat transfer coefficients were calculated and heat transfer coefficients in the tube side were determined. Three-dimension computation was performed to predict the flow and heat transfer performance in the finned tube. The effects of external fin height and pitch of the finned tube on shell-side flow and heat transfer were studied by numerical simulation.The influences of external fin height are strong on heat transfer and flow resistance. The heat transfer and flow resistance increase with the increase of external fin height. The influence of external fin pitch is weak on heat transfer, while is relatively strong on flow resistance under external fin pitch is compact.
Yongqing Wang et al. [6]The thermodynamics performances for tube banks in cross flow and for the shell sides of shell-and-tube heat exchangers were investigated, and the relation of fluid flow and heat transfer between them were analyzed. The results indicate that the incline degree of tube does not lead to obvious change on characteristics of fluid flow and heat transfer for fluid flowing across tube banks. Under different incline degrees of tubes, the characteristics of fluid flowing across tube banks are similar concerning fluid velocity components and local heat transfer along across angles.
S. Toolthaisong et al. [7] The experimental investigation of the air side heat transfer and pressure drop characteristics at steady state for the cross flow heat exchangers having flat tube configuration with staggered arrangement are presented. The effect of attack angles on the air side is major to study. In addition, the effect of tubes aspect ratios was also studied. Nineteen heat exchangers with four aspect ratios (0.18, 0.39, 0.66 and 1) and six attack angles (0 , 30 , 60 , 90 , 120 and 150) are investigated. The water temperature of 75 °C and the air at ambient condition flowed through the heat exchangers with velocity range from 2 to 6 m/s. The results show that the thermal and the pressure drop characteristics had governed by the attack angles and the tube aspect ratios. For all values of the air velocity of each tube aspect ratios, to increasing the attack angles (0-90) the heat transfer rate and the pressure drop were increased, while the thermal hydraulic performance was decreased. When considered effect of tubes aspect ratios on thermal and pressure drop characteristics, the results indicated that to change of the attack angles of lower tube aspect ratios had effected on thermal and pressure drop more than attack angle changed of higher tube aspect ratios.
Literature reviews show that for the heat exchanger boiler steam rate can be enhanced by the addition of the fins to the heat exchanger tube. The waste heat recovery system improves efficiency of the system.

3. Objectives

a) To study performance of waste heat recovery boiler.
b) To study the various methods to increase the heat transfer coefficient for waste heat recovery boiler.
c) To study the performance of waste heat recovery system with fins.
d) To enhance steam continuous steam rate from the waste heat recovery boiler, without damaging any coil.

4. Methodology

Methodology used for Numerical Simulation and validation with Experiment:



5. Numerical Analysis

5.1 Fluid Model Preparation

Fluid Model of the heat exchanger boiler is prepared as shown in Fig.1 from the provided solid model. It consists of water fluid layer as an outer part. Tubes and heater are modeled inside the heat exchanger. Water inlet is provided at mid height of heat exchanger. Tubes are placed below the water inlet. Heating coils are placed at bottom of heat exchanger. The outlet for the steam is as top of the heat exchanger.

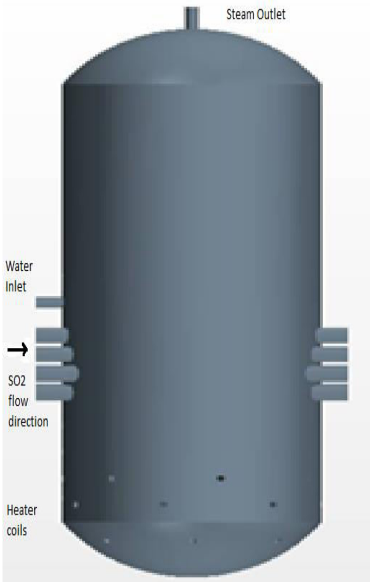


Fig.1 Fluid model for simulation

5.2 Mesh

All models are meshed using STAR CCM+ Preprocessing software. Since tetrahedra are much more efficient in terms of CPU and memory usage than other element topologies, tetrahedral mesh is used.

5.3 Assumptions

1. Flow is assumed Steady and Incompressible.
2. Heat exchangeris simulated using Volume of Fraction (VOF) concept.
3. SpalartAllmaras turbulence model has been used.
5. Thermo physical properties of air are constant and are considered at respective temperature flow analysis.

5.4 Boundary Conditions

1. All outside surfaces are considered as adiabatic wall. i.e. u=v=w=0, $k_i \frac{dT}{ds_i}$=0
2. No slip conditions at tube and shell surfaces.
3. Fluid properties are considered respective temperature.
4. Velocity of SO_2 is 0.663 m/s
5. Flow rate of water at inlet is 0.0009 kg/s.
6. Gravity is acting in –ve Z-direction.
7. Initial conditions, at t=0, u=v=w=0 m/s,

Pressure P =5 Bar

Eddy kinematic viscosity 0.0001 m^2/s

Fluid flows in loop, hence, no inlet and outlet. Pressure constraint is used as nodal boundary condition.

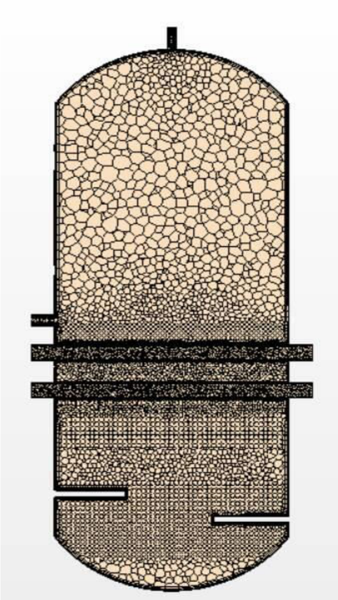


Fig.2 Meshed model

5.5Governing Equations

Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho \mathrm{v})}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

Momentum equation

$$\rho\frac{dV}{dt}=\rho g-\nabla P+\mu\nabla^2\mathrm{V}$$

Energy Equation

$$\rho\frac{\partial h}{\partial t}+\rho\boldsymbol{u}.\nabla h=\nabla.\boldsymbol{q}+\rho s$$

Where u is the velocity vector, h is the enthalpy.

5.6Simulation Results

This section represents the results of simulation with the boundary conditions, geometric models, mesh models, governing equations as specified in previous sections. In the initial phase, temperature distribution in heat exchanger is studied. Temperature counter is shown in fig.

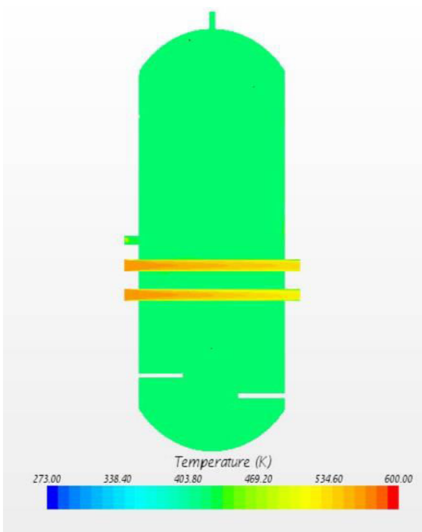


Fig.3 Temperature distribution in heat exchanger

From the temperature contour, it is observed that the temperature of the gas decreases as it passes in tube. Temperature of water is 425 K constant throughout shell.

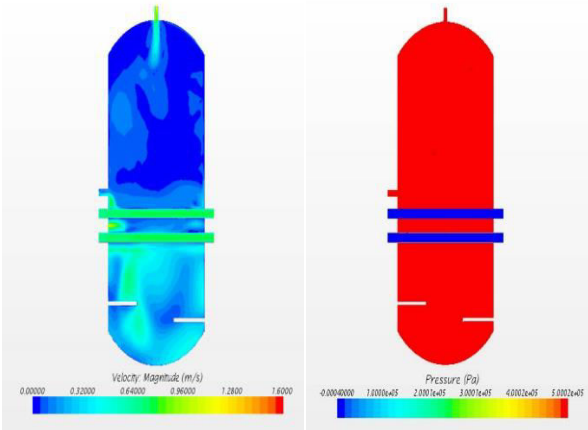


Fig.4 Velocity and Pressure Distribution in heat exchanger

The velocity of the hot gas is almost constant through the tube, except near tube wall.The velocity at water inlet and outlet is high.It is because of the area at outlet is converging. Pressure in heat exchanger is maintained at 5 bar. The pressure of gas inside tube is almost atmospheric.

Fig 5. Shows the vapor of fraction inside shell is in range of 0.9 to 1. The vapor of fraction at the top is high and it is less at the bottom part.

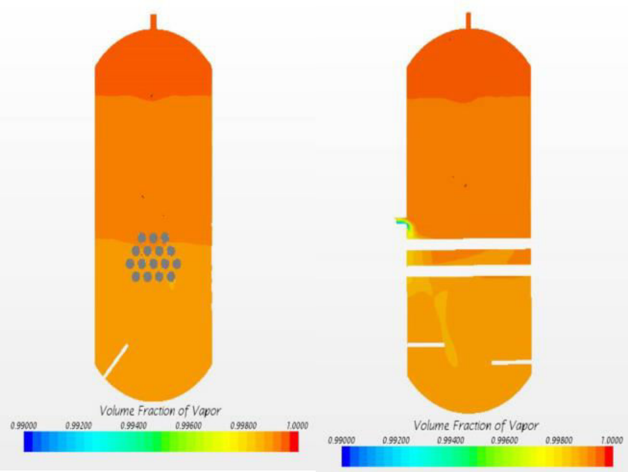


Fig.5 VOF in heat exchanger

6. Experimentation

The schematic diagram of experimental set up is shown Figure 6 and 7.showsthat heat recovery is done by the waste heat recovery boiler. It is fire tube boiler. The hot gas flows inside tube and cold fluid is outside the tube.

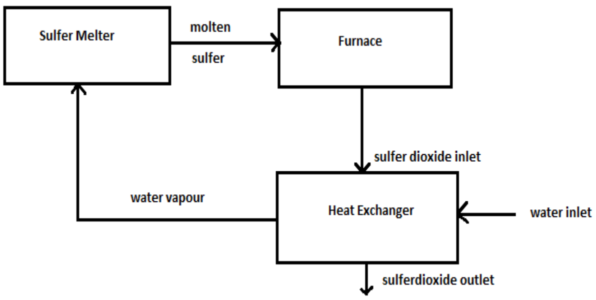


Fig.6 Block diagram of VAPCON system

The Sulfur Dioxide gas flows inside the tube which is at temperature 290-300 degree. Temperatu0re of the cold water is outside the tube is 70-80 degree. There are 16 number of tubes placed horizontally in the boiler. The tubes are placed in staggered arrangement. Each tube is of length 1.2 meter with 70 mm inside and 73 mm outside diameter. The mass flow rate of the Sulfur Dioxide gas is 200 kg/sec. The water flow is continuous in the waste heat recovery boiler. The water level is maintained at half of the boiler height. The outlet temperature of the sulfur dioxide is 230 degree. There are 21 electric heating coils which are used for the transient heating. The coils are of 2000 watt each. The coils are set at the bottom part of the boiler. The coils have cutoff temperature 150 degree. The required steam pressure is 5 kg/cm^2.
Thermocouple device is used to measure system temperature. Thermocouple is directly connected to the system. Three thermocouple are used in system, one thermocouple is measuring sulfur dioxide inlet temperature, second is used for sulfur dioxide outlet temperature measurement and third used for the water vapor temperature measurement.

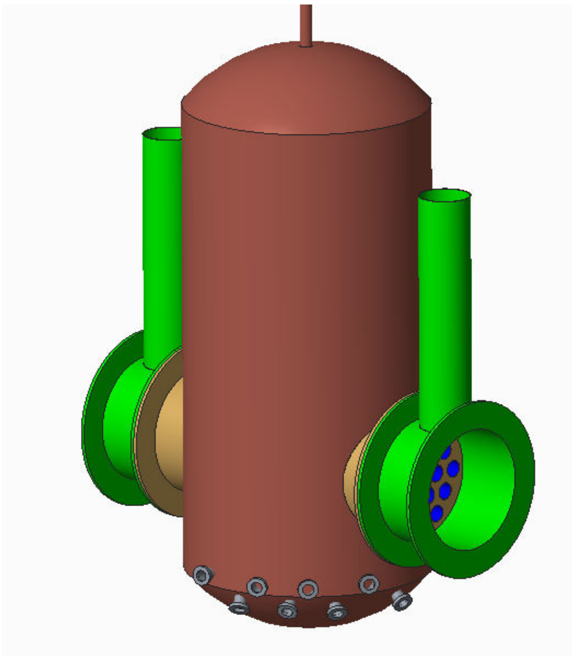


Fig.7 Waste heat recovery boiler

Table.1 Specification and quantity of instrument

Sr. No.	List of Equipment	Specification	Quantity
1.	heat exchanger	2.5 m height, 1 m diameter.	1
2	Heat exchanger tubes	L= 1.2m Di = 0.07 m Do =0.073 m	16
3.	Electric Heater	2kW	21
4.	Temperature measuring instrument	K-Thermocouple	3

Table.2 Observation table

Temperature	Inlet	Outlet
Hot gas	300°C	220°C
Cold fluid	80 °C	152°C
Pressure (after steady state)	5kg/cm^2	

7. Experimental calculations

7.1 Outside tube

Properties for water are calculated at mean bulk temperature.

$$Ra = \frac{g\beta(T_s - T_\infty)D_o\hat{}3}{\gamma^2} * Pr.$$

$$Nu = \{0.6 + \frac{(0.387\, Ra)\hat{}(1/6)}{[1+(0.559/Pr)\hat{}(9/16)]\hat{}(8/27)}\}^2$$

$$h_o = \frac{Nu * k}{Dh_o}$$

The values are calculated for outside the tube, the values are Ra =6791.57, Nu= 4.4034
h_o= 36.8558/m ºC.

7.2 Inside tube

The properties are calculated at mean bulk temperature of sulfur dioxide.

$$Re = \frac{V*D}{\gamma}$$
$$Pr = \frac{\mu\, Cp}{K}$$

From the formulae we get the value of
Re = 9596.2 Pr= 0.9
Relation used- Dittus-Boelter equation.

$$Nu= 0.023Re^{0.8}Pr^{0.3}$$
$$h_i=\frac{Nu*k}{Di}$$

The value of Nu = 31.7432and h_i= 8.61

7.3 Using fins outside

Using 100 fins with diameter 93 mm and thickness 2 mm.
Calculations with using fins
$r_{2c}=r_2+t/2$
$L_c=L+t/2$
$A_p=L_c t$
$$\xi= L_c^{3/2}\left(\frac{h}{kA_p}\right)^{1/2}$$

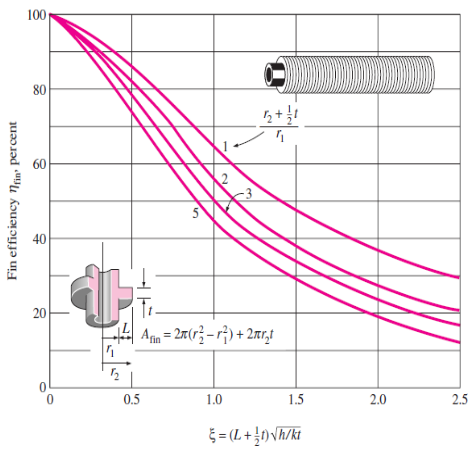


Fig.5 Efficiency of circular fins of length L and constant thickness t [8]

For unfin portion
$Q=hA(T_b - T_\infty)$

For fin
$Q_f= \eta_f h A_f(T_b - T_\infty)$

Total
$Q_t = n(Q_f + Q)$

Fin effectiveness
$$\varepsilon=\frac{Q_t}{Q_{without\ fin}}$$
From calculations Q_f =7400 W,$Q_{without\ fin}$ =2394 W and ε = 3

7.4 Fins inside tube

Using the fins inside the tube, number of fins are 8 and of 30 mm height.
$$A_c=\left(\frac{\pi}{4}\right) d_i^2\text{-NHt}$$
$$D_h=4\,\frac{\left[\left(\frac{\pi}{4}\right)d_i^2 - N\,H\,t\right]}{(\pi d_i+2N\,H)}$$

From calculation we get Nu = 106.17 and h_i=131.43 W/m°C.

8. Results and Discussion

Table1 represent the comparison of simulation and experimental results. There is a small variation between experimental and simulation values of temperature at tube outlet. Temperature valueis less in experiment than simulation. The reason may be temperature losses which is not considered while numerical simulation.

Table.3variations between simulation and experimental results

	Experimental	Numerical
Temperature tube outlet	493 (k)	497 (k)
Heat transfer coefficient tube inside	8.3892 W/m^2K	8.415W/m^2K
Heat transfer coefficient tube outside	36.855 W/m^2K	36.7 W/m^2K

7. Conclusion

This work investigates the heat transfer from the hot gas to the water. The heat transfer coefficient for the heat exchanger investigated using numerical and experimental calculation. From that it is found that the heat transfer coefficient inside the tube of heat exchanger is less as compared to outside, because of that the steam generation is less. The remedy for the less steam generation would be attaching fins to tube to improve the heat exchanger steam generation. The theoretical calculations for fins are shown, attaching fins can enhance heat transfer.

Acknowledgment

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