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Comparison of Heat Transfer Performance of Plain Tube and Rifled Tube by Experimentation and CFD Analysis

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ABSTRACT

Modification of surface geometry of heat transfer surface is one of the effective methods of heat transfer augmentation. Advantages of rifled tube over plain tube are main objective of the present study for consideration of replacement in fire tube boiler. Flue gas side surface heat transfer coefficient is the criteria used for the comparision. Heat transfer performance of helically ribbed tube (Rifled Tube) is compared with that of plain tube experimentally. The experimental methodology, experimental set up and the comparison results are presented in this paper. Gas side surface heat transfer coefficient for plain and rifled tube is evaluated and presented in this study. An experimental result proved that 80% enhancement in heat transfer coefficient is observed. CFD Analysis is done for temperature profile of plain tube and rifled tube.

Keywords: Enhancement, Heat transfer coefficient, Rifled tube, Plain tube, CFD analysis.

1. INTRODUCTION

In the convection section of a typical tube of fire tube boiler, 90% of the resistance to heat transfer from the flue gas to the water on the shell side, is on the inside of the tubes. Decreasing this resistance (i.e. increasing inside heat transfer coefficient) by using helically ribbed tubes significantly increases the overall heat transfer in the convection section. The rifled tubes are used in boilers and heat exchangers for efficient results in terms of heat transfer. The internal ribs introduce the centrifugal force inside the tubes. The advantage of the rifled tube compare to smooth tube is that it will cause the swirling effect in the flow. Due to its inner geometry shape, flow is thrown outwards to the tube wall as a result of centrifugal action. Thus, creates a secondary flow or also known as helical flow or a swirl flow at the near wall region. This helical flow at the tube periphery superimpose on the main axial flow. This effect enhance wall wetting and prevents critical heat transfer occurrence even under high steam void fraction conditions and lower critical heat flux. As a result, this type of tube would not easily burnout and can be used under much higher operating condition than the plain tube.

Smith, J. W. et al. [1]: The objective of this study was to experimentally measure the turbulent heat transfer and temperature profiles in a rifled pipe. The rifled pipe was made by fitting snugly the continuous spiral rib inside a smooth brass tube which had the inner diameter of 2.058 inch. The temperature profiles showed that the rifling had reduced the resistance to heat transfer in the turbulent core which in the end the rifled tube offered a much better heat transfer efficiency than in the smooth tube. Due to relatively uniform temperature profiles in the rifled tube, the authors had suggested that the application of the rifled tube in tubular type reactors to ensure uniform temperature distribution. **Zarnett, G. D. & Charles, M. E. et al. [2]:** The objective of this study was to carried out experimental work to observe the flow patterns of two phase flow in horizontal tubes fitted with internal spiral tubes (rifled tube) which their pitch to diameter ratios is 1.57 and 2.79 respectively. Besides that, comparison of single phase friction factor between smooth tube and the two rifled tubes also have been done which showed that the friction factors for the two rifled tubes were larger than the smooth tube. Correlations for friction factor also have been established for the two rifled tubes. **Han, J. C. et al. [3]:** The objective of this study was to carried out investigation on rib-roughened surface to determine the effect of rib shape, angle of attack and pitch to height ratio on friction factor and heat transfer. The thermal hydraulic performance of the tested ribs was at optimum when angle of attack near 45°. **Kohler, W. &**

Kastner, W. et al. [4]: The objective of this study was to investigate the effect of internal rifling on heat transfer and pressure loss under high pressure in rifled tube. The experimental parameters like pressure, mass velocity, and heat flux are ranging from 50-220 bar, 500-1500 kg/m²s, and 0-600kW/m² respectively. The flow orientation in this experiment is vertical up flow. The rifled tube that is used in this experiment have outer diameter, 25.4 mm, equivalent inner diameter, 13.25mm, number of ribs, 4, rib width, 3.5mm, rib height 0.775mm and helix angle 58°. The rifled tube is made of SA-213 GRADE T11 (ASME). In the heat transfer investigation, the internal rifling had caused the boiling crisis and post Critical Heat Flux (CHF) regime shift towards higher steam qualities comparing to smooth tube. The maximum wall temperature is much lower in the rifled tube than smooth tube. The pressure loss in the rifled tube also had been investigated for single phase and two phase flow which shows two folds than the smooth tube. It is found out that the thermal non equilibrium in the un wetted region does not occurred (due to swirl flow) in the rifled tube. **Weisman, J. et al. [5]:** The objective of this study was to carried out an experimental examination on two phase flow patterns and pressure drop in single and double helically ribs. In this experiment, helical wire ribs have been inserted into two tubes which had the diameter of 2.54cm and 5.10cm, respectively. The helical wire ribs had the height of 0.32, 0.64 and 1.27cm, while the helical twisted ratios are 1.2, 2.1, 2.3 and 2.5. It is concluded that when a minimum flow velocity is exceeded, not only swirling occurred; the enhancement of the critical heat flux would also occurred. The authors had proposed correlations for predicting the onset of swirling annular flow which can be used for air-water systems flowing in tubes with diameter between 1cm - 5cm and where the liquid velocity is in range between 0.1m/s and 0.5m/s while the gas velocity is in range between 0.2m/s and 25m/s.

The present study is based on the procedure of circulating the water and gas in an experimental set up at different inlet temperatures and mass flow rates to determine heat transfer coefficient.

2. EXPERIMENTAL METHOD

2.1 Experimental set up

Fig.1 shows the detail of the test section and Fig. 2 shows the experimental set up to determine the heat transfer coefficient.

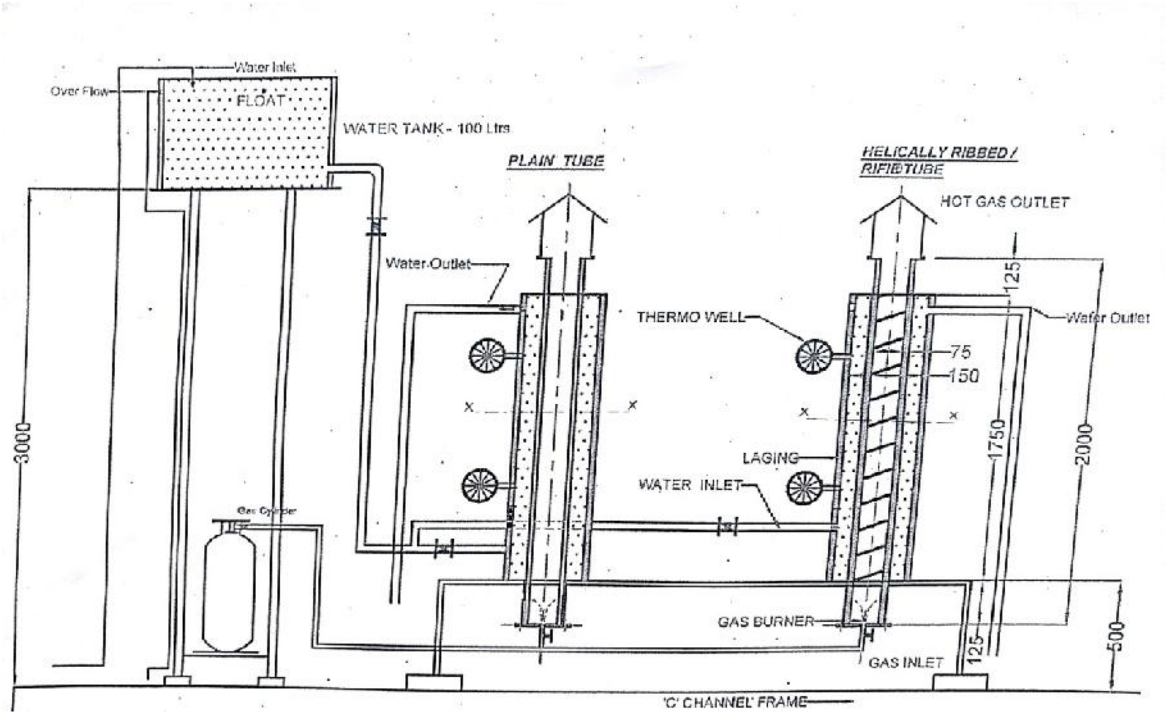

Fig.1 Details of test section

Fig.2 Experimental set up

Water is passed from the water tank through annular space between outer tubes of diameter 150 mm and inner tube. LPG gas is fired by using T type Zinc burners. The fired gas is passed through the inner plain tube and rifled tube having inner diameter 75mm and length 1750 mm. The material used for tubes is BS 3059 ERW. The piping material is IBR, BS 3059 ERW. Eight K (Chromel-Alumel) type thermocouples are mounted at the inlet and outlet section of plain tube and rifled tube for measuring inlet and outlet temperatures of water and gas. The mass flow rate of water is measured by collecting the water in measuring buckets in a particular time.

2.1.1 Calibration of thermocouples:

K type thermocouples are used for measurement of temperatures at different locations. Thermocouples are calibrated at ice point and steam point. The temperature measured by thermocouple at ice and steam is compared with calibrated mercury filled thermometer. A fixed error of 2ºC is observed at both the fixed point. Also the temperature is measured randomly at two points in between ice and steam points by thermocouple and thermometer shown same error of 2ºC. Measured uncertainty matched with that supplied by manufacturer. Fig. 3 shows cross section of the thermocouple mounting in experimental setup.

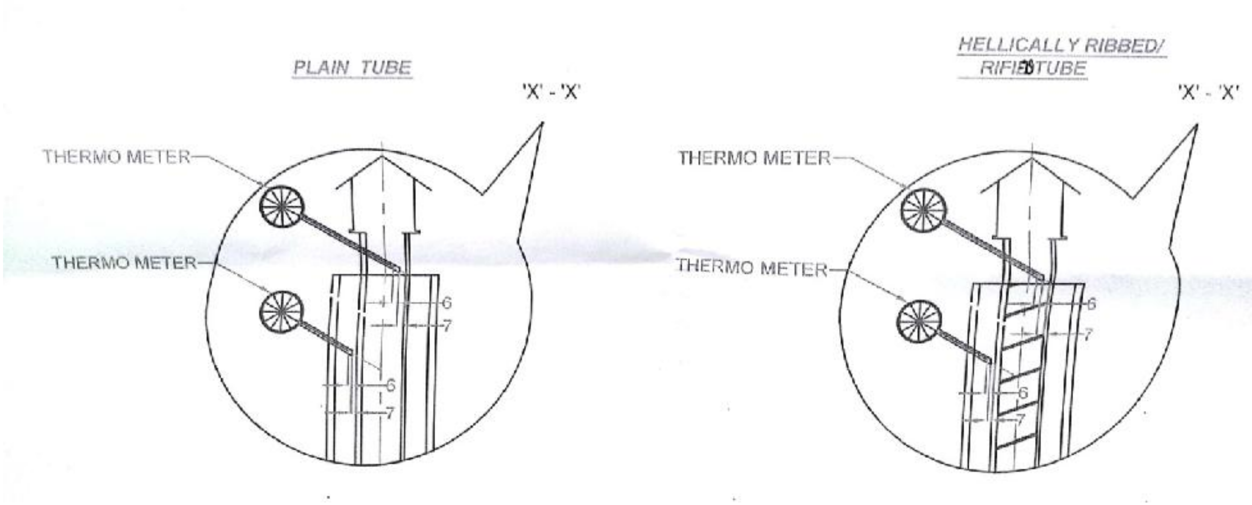

Fig. 3 Thermocouple Mounting

2.2 Experimental procedure

Experiments at different mass flow rates of water and gas are performed. The mass flow rate of gas varies from 0.008 Kg/s to 0.01 Kg/s. The mass flow rate of water varies from 0.02 kg/s to 0.07 kg/s. The observations at steady state condition for inlet and outlet temperatures of water and gas through the plain tube and rifled tube are noted. The thermophysical properties at bulk mean temperature are collected. Following is the step-by-step procedure to determine Reynolds number and heat transfer coefficient.

Step 1. Heat gained by water (Q_w) is estimated from Eq. (1)

$$Q_w = m_w C_{w} (T_{o} - T_{i}) \quad (1)$$

Step 2. Heat given by gas (Q_g) is estimated from Eq. (2)

$$Q_w = Q_g \quad (2)$$

Step 3. Logarithmic mean temperature difference (Δ_{L}) is estimated by Eq. (3)

$$\Delta_{L} = \frac{(T_{i} - T_{i}) - (T_{o} - T_{o})}{\ln[(T_{i} - T_{i})/(T_{o} - T_{o})]} \quad (3)$$

Step 4. Overall heat transfer coefficient (U_0) is estimated by Eq. (4)

$$U_0 = \frac{Q_T}{\pi D_0 L \Delta_{L}} \quad (4)$$

Step 5. Velocity of water (V_w) is estimated by Eq. (5)

$$V_w = \frac{4 m_w}{\pi \rho_w [D_o^2 - D_i^2]} \quad (5)$$

Step 6. Reynolds number of water (R_w) is estimated by Eq. (6)

$$R_w = \frac{\rho_w V_w (D_o - D_i)}{\mu_w} \quad (6)$$

Step 7. Prandtl number of water (P_w)is estimated by Eq. (7)

$$P_w = \frac{\mu_w C_w}{k_w} \quad (7)$$

Step 8. Nusselt number (N_u) is estimated by Eq. (8)

$$N_u = 3.66 + \left[\frac{0.0 \; R \; P \; (D/L)}{1 + (0.0 \; (R \; P \; (D/L))^{0.6})}\right] \quad \text{[Ref. 21]} \quad (8)$$

Step 8. Outer surface heat transfer coefficient (h_0) is estimated by Eq. (9)

$$h_0 = \frac{N_u K}{(D_o - D_i)} \quad (9)$$

Step 9. Inner surface heat transfer coefficient (hi) is estimated by Eq. (10)

$$\frac{1}{U} = \frac{1}{ho} + \frac{\ln(\frac{r}{r})}{2\pi} + \frac{1}{hi} \quad (10)$$

2.3 CFD Analysis

The CAD model is designed in CATIA V5R19. The meshing is done in ICEM CFD 16.0 after modeling, the total number of elements is 2077644 and the total number of nodes is 467785 for Plain Tube and the total number of elements is 8592287 and total number of nodes is 1802255 for rifled tube. The element type is tetrahedral type. In order to capture both the thermal and velocity boundary layers the entire model is discretized using tetrahedral type mesh elements which are accurate. Fine control on the mesh near the wall surface allows capturing the boundary layer gradient accurately. The entire geometry is divided into two fluid domains i.e. Fluid Flue gases and Fluid Water. In the present study, the k-epsilon Realizable model is used with near wall treatment having standard wall functions. The solving is done in FLUENT 16.0 and post processing is done in CFD-Post 16.0. The Fig.4 and Fig.5 shows the mesh of plain tube and rifled tube.

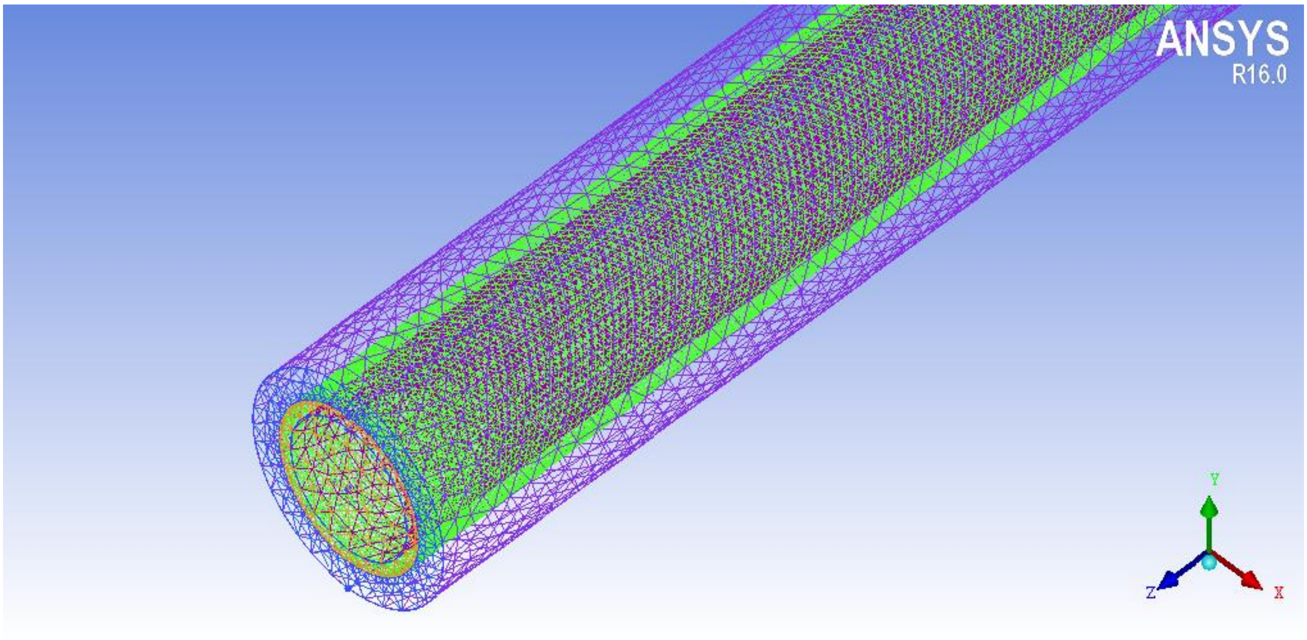

Fig. 4 Mesh of Plain tube with wireframe display.

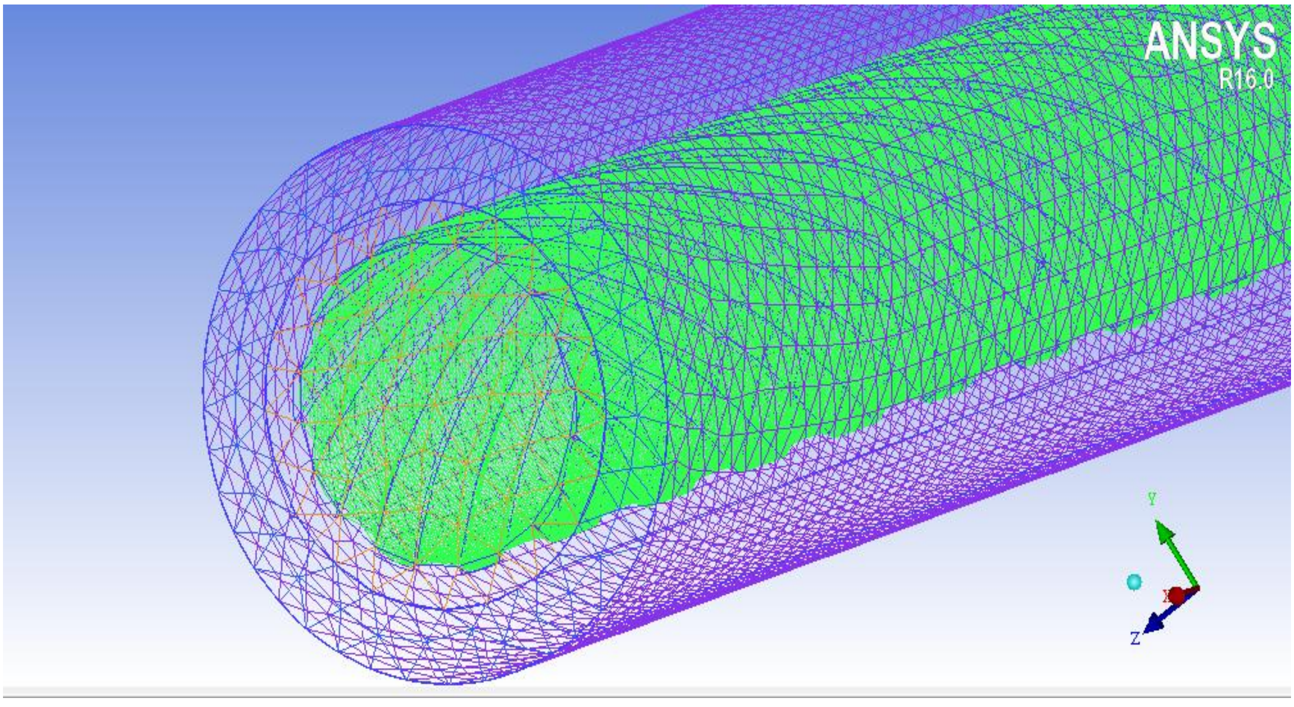

Fig. 5 Mesh of rifled tube with wireframe display

3. RESULTS AND DISCUSSION

With experimental observations, the heat transfer coefficient of plain tube and rifled tube is determined as per the procedure explained in Sec. 2.2 of this paper. The Fig.6 to Fig.12 gives the comparison of heat transfer performance for plain tube and rifled tube at different mass flow rates of water and gas. CFD analysis gives the temperature profile of plain tube and rifled tube as shown in Fig. 13 and Fig. 14.

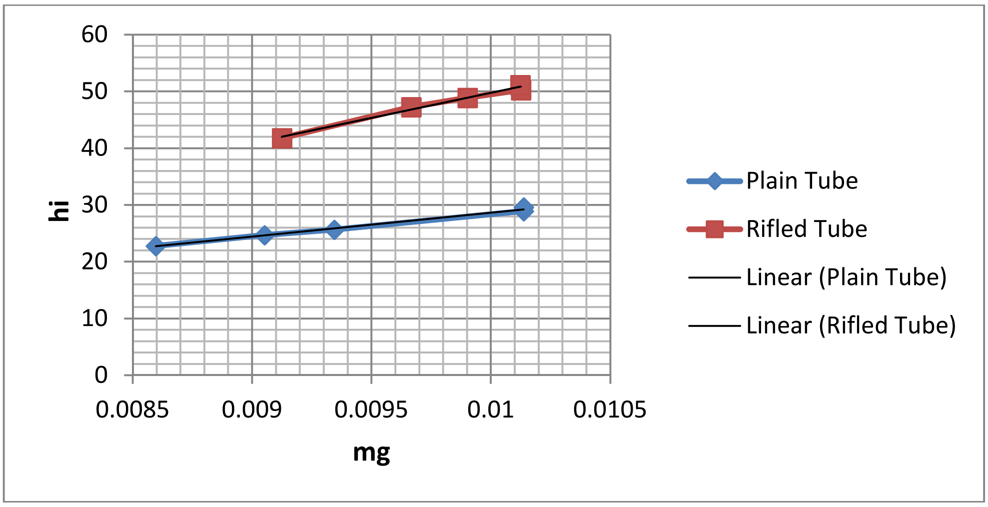

Fig.6 mg vs hi for mw 0.02 kg/s

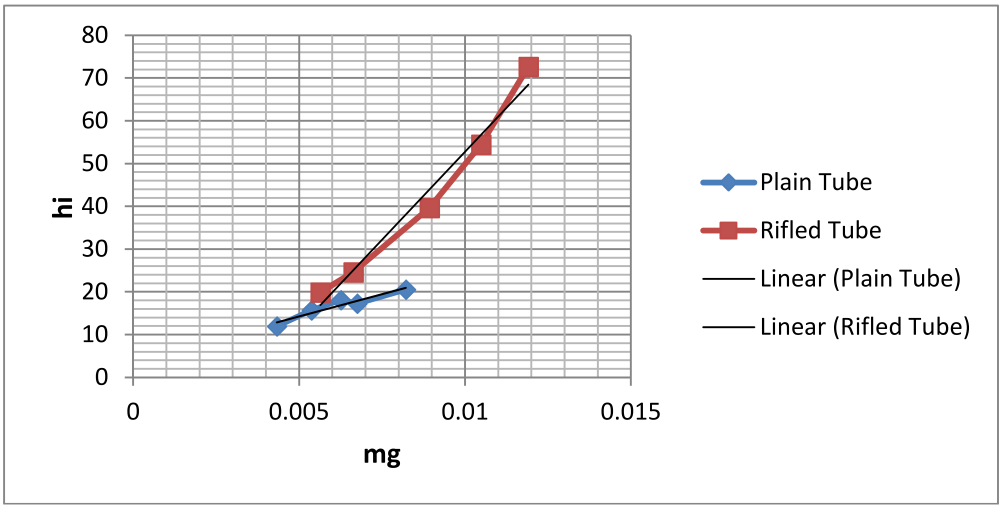

Fig. 7 mg vs hi for mw 0.033 kg/s

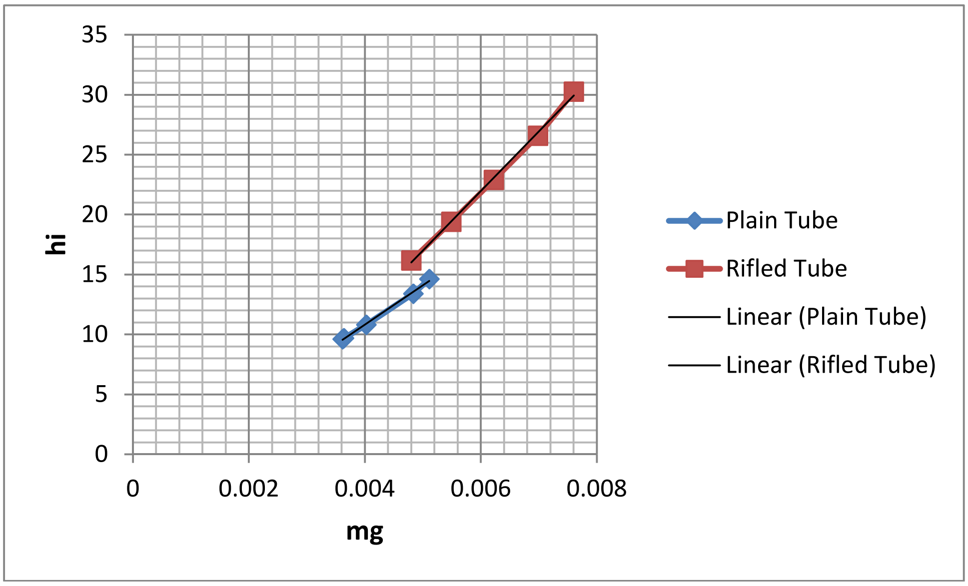

Fig. 8 mg vs hi for mw 0.037 kg/s

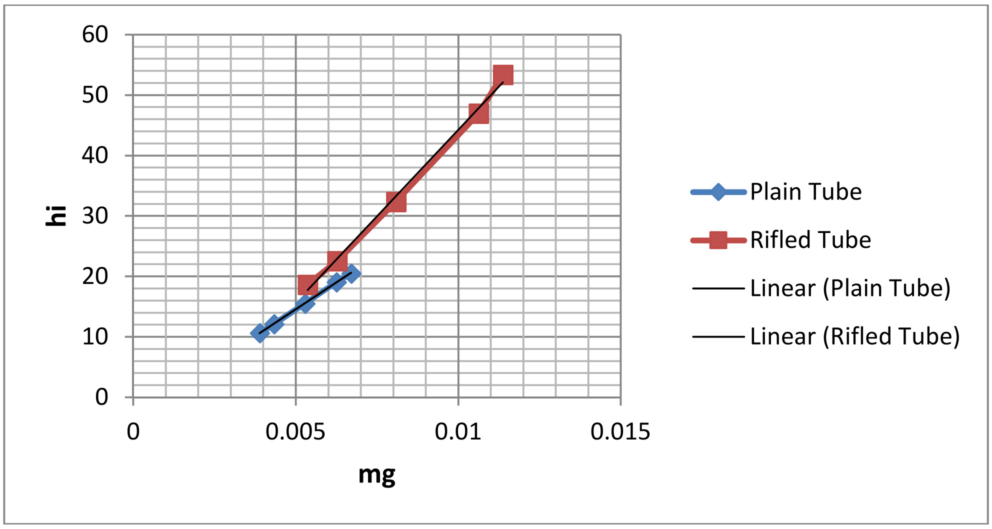

Fig. 9 mg vs hi for mw 0.045 kg/s

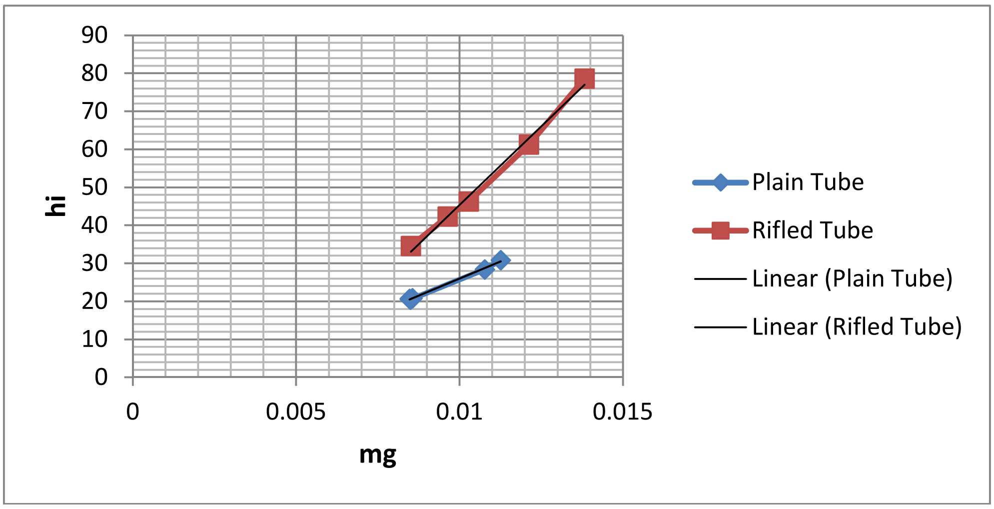

Fig. 10 mg vs hi for mw 0.06 kg/s

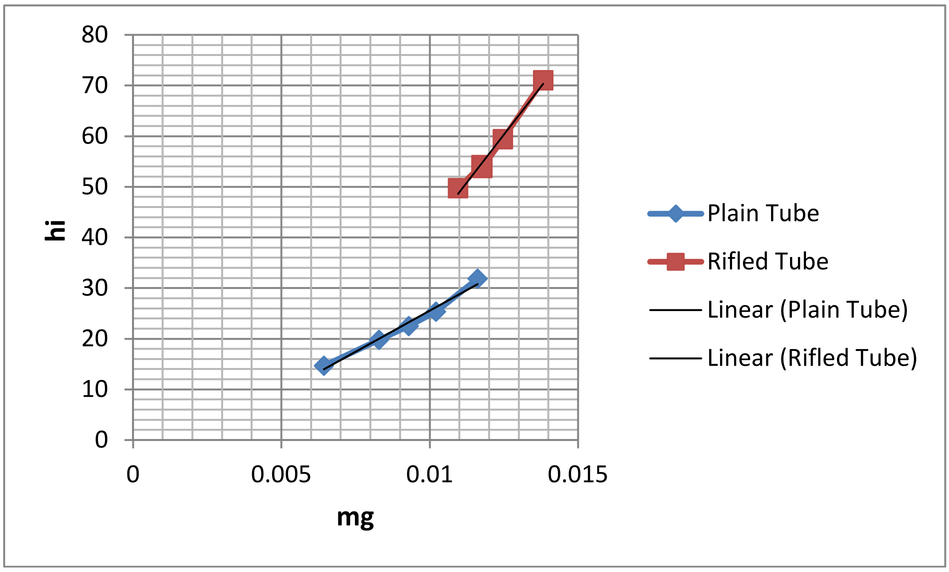

Fig. 11 mg vs hi for mw 0.075 kg/s

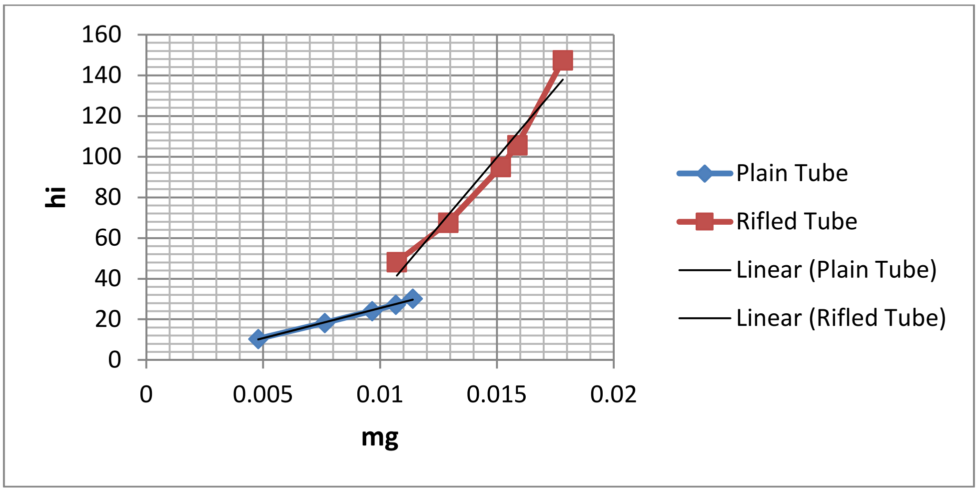

Fig. 12 mg vs hi for mw 0.079 kg/s

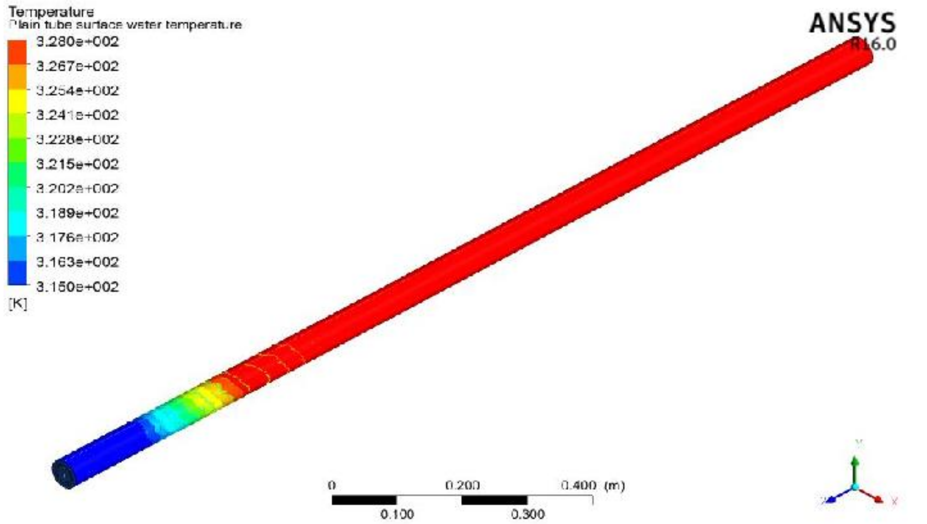

Fig. 13 Plain tube surface water temperature contour at mw=0.079 kg/s and mg=0.01 kg/s.

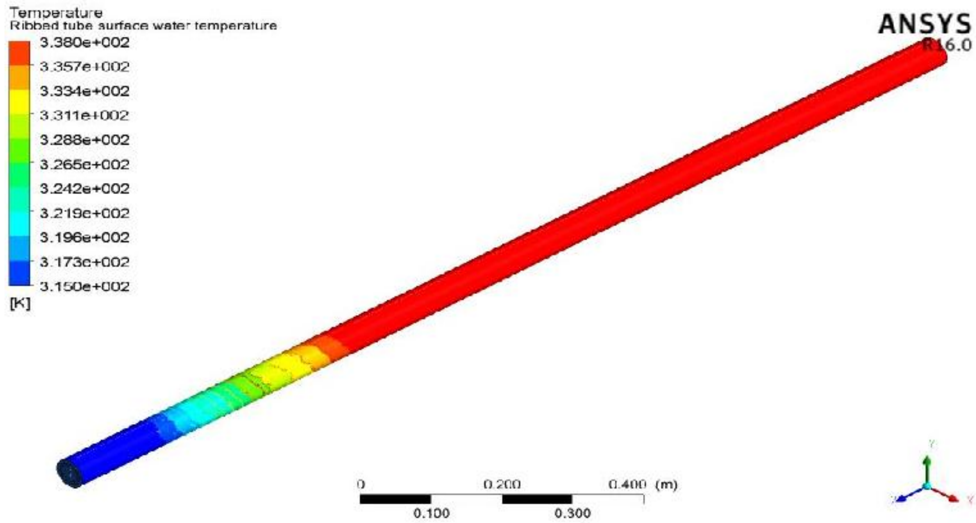

Fig. 14 Rifled tube surface water temperature contour at mw=0.079 kg/s and mg=0.01 kg/s.

Figures indicate that heat transfer enhancement increases with the use of rifled tube. The internal ribs introduce the centrifugal force inside the tubes. The advantage of the rifled tube compare to plain tube is that it will cause the swirling effect in the flow. Due to its inner geometry shape, flow is thrown outwards to the tube wall as a result of centrifugal action. Thus, creates a secondary flow or also known as helical flow or a swirl flow at the near wall region. So the Reynolds number of gases through rifled tube is more than plain tube. Hot flue gases enter plain tube and remain to a laminar or straight flow so the boundary layer forms along the plain tube walls, retarding heat transfer. Hot flue gases enter rifled tube in turbulent pattern and remain turbulent. Precisely designed ribs keep hot flue gases in turbulent flow. Hence the inner surface heat transfer coefficient of rifled tube is more than plain tube.

4. CONCLUSION

From experimental results of comparison heat transfer performance of plain and rifled tube, following conclusions are taken out.

- Heat transfer coefficient on both, waterside and flue gas side, increases as per mass flow rate, this is very common trend that is followed as per present heat transfer theory.
- Enhancement of 80% is observed in inner side heat transfer coefficient for rifled tube over plain tube.
- Enhancement of 56% is observed in overall heat transfer coefficient for rifled tube over plain tube
- Rifled tubes are more suitable for fire tube boilers than plain tubes which will make boiler compact and more efficient.
- According to CFD analysis, the rifled tube surface water temperature is more than the plain tube surface water temperature.

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Nomenclature

mg: Mass flow rate of gas (kg/s)
mw: Mass flow rate of water (kg/s)
Tgi: Inlet temperature of gas (°C)
Tgo: Outlet temperature of gas (°C)
Twi: Inlet temperature of water (°C)
Two: Outlet temperature of water (°C)
Cpw: Specific heat of water (J/kg K)
Kw: Thermal conductivity of water (W/m K)
ϱw: Density of water (kg/m^3)
µw: Viscosity of water (Pa s)
Qw: Heat transfer rate of water (J/s)
ΔTlmtd: Logarithmic mean temperature difference (°C)
Uo: Overall heat transfer coefficient (W/m^2 K)
Vw: Velocity of water (m/s)
Rew: Reynolds number of water
Pr: Prandtle number of water
Nu: Nusselt number of water
ho: Outer surface heat transfer coefficient (W/m^2 K)
hi: Inner surface heat transfer coefficient (W/m^2 K)
Cpg: Specific heat of gas (J/kg K)
ϱg: Density of gas (kg/m^3)
µg: Viscosity of gas (Pa s)

Kg: Thermal conductivity of gas (W/m K)
Vg: Velocity of gas (m/s)
Reg: Reynolds number of gas
Prg: Prandtle number of gas
(Nu) g: Nusselt number of gas

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