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Heat Transfer Enhancement for Single Phase Turbulent Flow in Horizontal Tube Using Corrugation: A Review

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ABSTRACT

Plain tube is most commonly used in heat transfer units for heat exchange. Little modification of roughing the tube with no much additional cost and manufacturing hurdle can improve heat transfer is the need of the present era. Use of corrugation in the tube serves the purpose of heat transfer enhancement with moderate pressure drop penalty. The review of such investigation on passive method of heat transfer enhancement is necessary. In the present study reviews of work of various investigator is done and ready reference summary is prepared. The study will useful for the quick reference of heat transfer enhancement technique with corrugated tube for turbulent single phase flow.

Keywords : Corrugation, Heat Transfer Enhancement, Passive Method

NOMENCLATURE

Symbol	Definition
d	Tube diameter, mm
e	Height of roughness element, mm
h	heat transfer coefficient
p	Distance between two adjacent roughness elements, pitch, mm
l	Length of the tube, mm
q	Heat flux, W/m^2
Q_{conv}	Convection heat loss
Q_{rad}	Radiation heat loss
T_f	Bulk fluid temperature
T_w	Wall temperature
$\propto$	Helix angle
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

I. INTRODUCTION

Heat exchanger is the most common device used in power plant, process industries, refinery, chemical industry, textiles industries, pharmaceutical industries etc. Heat exchanger mostly uses plain tube for the flow of fluid and heat exchange surfaces.

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There are two mechanism by with we can improve the heat transfer performance of heat exchanger. One such technique is active methods where additional power is required to achieve enhancement of heat transfer another one is passive heat transfer enhancement technique which do not require additional power. One of the passive augmentation techniques is providing roughness to the tube using corrugation. This method can easily replace plain tube as it does not involve complex manufacturing and significant cost of tube. Corrugation will help in better mixing of fluid at it increases turbulence and hence heat transfer characteristics improves. In the present study reviews of investigation on corrugation tube with reference to heat transfer characteristics is explored.

II. EXPERIMENTAL SETUP

Typical set up for the experimental test facility with verities of working fluid used for the heat exchanger units is given in this section with most common configurations.

General Experimental set up

The test facility that provides experimental investigation on heat transfer coefficient when fluid passes through the test channel is given in the Fig.1. The basic devices that uses in the test set up includes temperature measurement of working fluid at inlet of the test section with the thermocouples or any other suitable temperature sensors. Temperature measurements at various locations of the test channel. Thermocouples can be placed at various axial locations as well as at given axial location it can be placed at different circumferential locations as well. Large number of thermocouples can be placed if we need local data or we can use thermocouples or any other temperature sensors at the inlet and outlet locations of the test channel. Pressure gauge needed to measure system pressure at the inlet of the test channel. It also needed differential pressure transmitter to measure the pressure drop across the test channel. It can use suitable pressure sensing devices as per the range of the experimentation. A suitable flow sensing device is needed to measure the flow rate of working substance that flow through the system steadily. To flow the fluid through the system, there is need of suitable pumping devices. The pumping devices may be either pump of suitable range for the liquid flow or may be compressor for the vapour or gaseous fluid flow or may be blower can be used. Once heat is transferred to the fluid, the fluid can be discharged to the sump or it can be cooled and can be reused in recirculated. When there is closed system of flow we also need cooling loop to bring the working substance to the original state. In case of open system there is no need of cooling loop; heated fluid can be directed to the sump. There is need of suitable heat supply mechanism to the test section. Heating mechanism used may consists of heating coil or Joule heating can also be used in such condition test section is heated by providing electric current. The suitable valve must be provided to ensure and regulate the flow of working fluid through the system and to perform operations at different mass flow rate conditions. The data logger system can be installed for the recording of all the instruments.

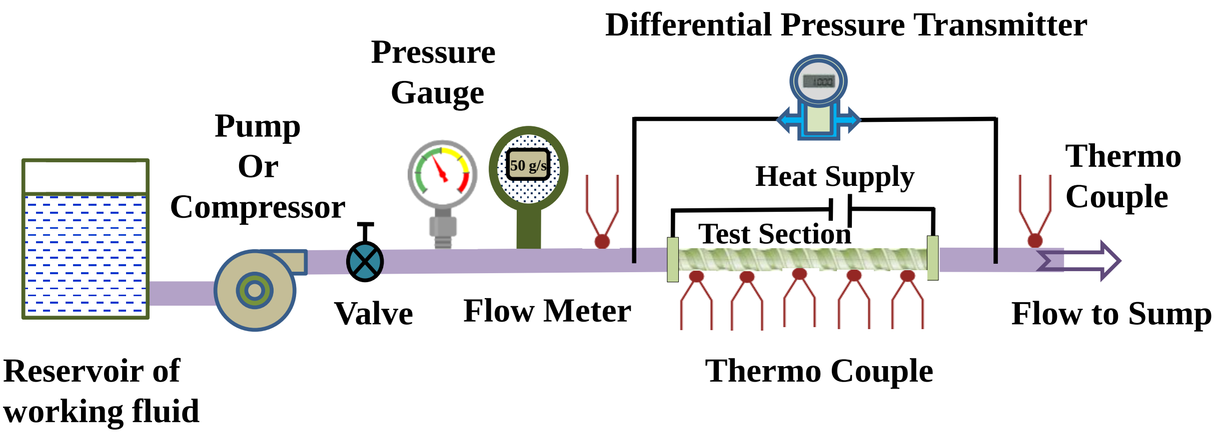


Fig. 1 Test setup for the experimental investigation of heat transfer coefficient in horizontal tube with groove

Working of the test set up

The first step is to check the reservoir for the sufficient quantity of the fluid present. The pump is started and test set up is run for a while to make sure for the smooth running of the set up. Then requisite flow rate can be set using the valve. The flow rate can be checked using flow meter. Once it ensures the requisite flow through the system, test section will be heated and then heating is adjusted up to the desired heat supply conditions. Measurement of all the instruments is done at given mass flow rate conditions. The measurement of experimental parameters includes measurements of temperature, pressure, pressure drop, mass flow rate etc. All the devices can be synchronised with the data logger to record the data of experimental parameters.

Test Section

Test section used can have groove of various size and shape, like circular, rectangular, square, elliptical etc., or corrugation. Test section may contain different pitch and depth of groove. Another variables of test section have are length of test sections, cross sections of test sections etc.

III. DATA REDUCTION

For calculating heat transfer coefficient for the tube, it is necessary to find out how much heat actually transfers to the fluid from the test section. So, from the given heat to the test section heat loss to the surrounding is to be finding out if it is the bare test section. Test section may be provided with effective insulation in such case heat supplied will be considered as heat given to the working fluid. Heat absorbed by the working fluid is dived by the heat transfer area to get the heat flux. Heat flux is divided by the temperature different to get the heat transfer coefficient as per the Eq. 3

$$q = \frac{Q_{effective}}{\pi dL} = \frac{Q - Q_{l\_net}}{\pi dL} \qquad \text{(Eq.1)}$$

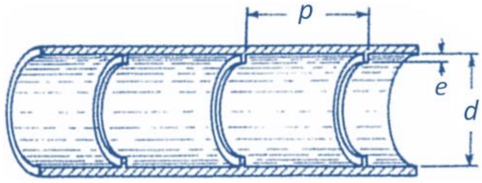
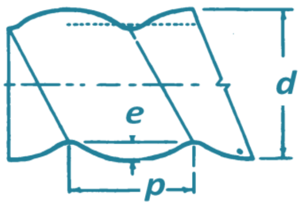
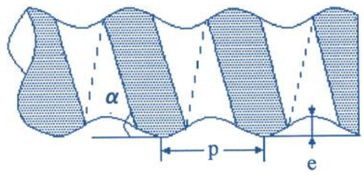
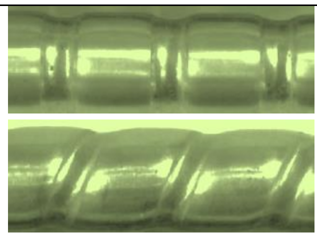
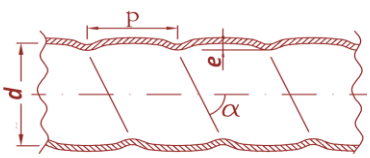
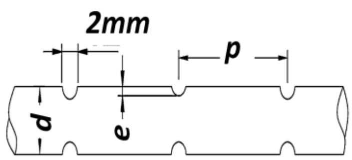
$$Q_{l\_net} = Q_{rad} + Q_{conv} \qquad \text{(Eq.2)}$$

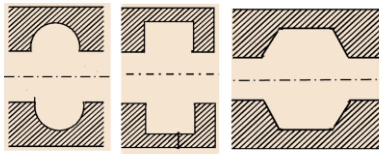
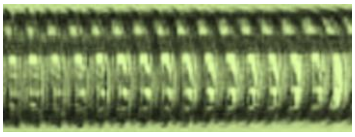
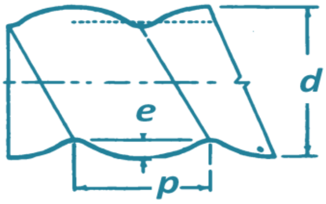
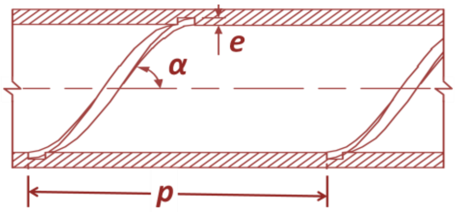
$$h = \frac{q}{T_w - T_f} \qquad \text{(Eq.3)}$$

IV. REVIEW ON THE CORRUGATION IN THE HORIZONTAL TUBE

Corrugation provided in the tube creates disturbance to the flow enhancing turbulence and provide better mixing of the fluid and hence increases the heat transfer rate. Investigations of heat transfer using corrugated tube is summarised as follows. Table 1. also gives summary of parameter used in the experiments.

Table 1. Summary of the contributors of the work on corrugated tubes for the heat transfer in single phase flow

Author	Parameter of the study	Sample geometry
R. L. Webb [1]	$0.01 < e/d < 0.04$ $10 < p/e < 40$ $0.71 < e/d < 37.6$ $6000 < Re < 100000$ $0.71 < Pr < 37.6$ Fluid: Air, water and n-butyl alcohol	
Withers [2]	$0.0311 < e/d < 0.0399$ $10.977 < p/e < 14.706$ $0.457 < p/d < 0.612$ $10000 < Re < 120000$ $2 < Pr < 11$ Fluid: Water	
Wang et al [3]	$e = 0.25\ mm$ $p = 15.6\ mm$ $d = 13\ mm$ $12500 < Re < 44000$ Fluid: Water	
Rainieri and Pagliarini [4]	$90 < Re < 800$ $16 < p < 64$, *Helical* Corrugation $16 < p < 32$, *Transverse Corrugation* $550 < q < 14300, W/m^2$ Fluid: Ethylene glycol	
Vicente et al [5]	$0.0267 < e/d < 0.0572$ $0.608 < p/d < 1.229$ $2000 < Re < 90000$ $2.5 < Pr < 100$ $d = 18\ mm$ Fluid: Water, Ethylene glycol	
San and Huang [6]	$0.015 < e/d < 0.143$ $0.304 < p/d < 5.72$ $4608 < Re < 12936$ $l/d = 87$ Fluid: Air	

Bilen et al [7]	$10000 < Re < 38000$ $l/d = 33$ Groove : Circular, rectangular and trapezoidal Fluid: Air	
Pethkool et al [8]	$0.02 < e/d < 0.06$ $0.18 < p/d < 0.27$ $5500 < Re < 60000$ $d = 23, 24, 25\ mm$ Helically corrugated tube Fluid: Water	
García et al [9]	$0.074 < e/d < 0.114$ $0.906 < p/d < 1.173$ $20 < Re < 20000$ $d = 16, 18\ mm$ Helically corrugated, dimpled and wire coiled tube	
Aroonrat et al [10]	$e = 0.2\ mm$ $12.7 < p < 305$ mm $4.2° < \alpha < 60°$ $q = 3500\ W/m^2$ $4000 < Re < 10000$ $d = 7.1\ mm$ Internal helical grooved tube Fluid: Water	

Webb [1] introduced roughness to the tube using corrugation to investigate for the heat transfer and pressure drop. Webb [1] concluded that heat and momentum transfer analogy correlates the experimental data of heat transfer using the rib test channel over the wide range of $e/d, p/e$ and Prandtl number. Correlations for the friction and heat transfer were developed for tube with roughness using repeated-rib. The experimental result obtained is supported by prior work on roughness created by sand-grain and this correlation can be applied to roughness geometry created by other means.

Withers [2] carried out work in tube with helical ridging for single phase fluid in turbulent/ transitional zone with water. Developed correlation of friction factor for single helix corrugated tubes using curve fitting method. In his study though it did not involves fully rough friction factor yet work was successful of getting enhancement of heat transfer up to the ratio of 3.

Wang et al [3] worked for heat transfer on spirally fluted carbon steel tube for high system pressure. Comparison was made for carbon steel smooth tube with copper tube, carbon steel spirally fluted tube with copper spirally fluted tube and copper smooth tube. The work shows the heat transfer performance of carbon steel fluted tube is similar to plain copper tube. So, plain copper tube can be replaced with carbon steel fluted tube. The work also shows that carbon steel spirally fluted tube gives better heat transfer performance compared to plain carbon steel tube.

Rainieri and Pagliarini [4] performed experimental study to test helical and transverse corrugated tube to investigate heat transfer and its mechanism in the thermal entry region. The parameters used are given in Table 1 with four different corrugation pitches. There is significant swirl created with helical corrugation but that will not result into corresponding heat transfer enhancement. No significant effect on heat transfer in the hydrodynamic entrance region. Transverse corrugation is more effective in enhancing heat transfer than helical corrugation as it prompts transition from laminar to turbulent. As far as fabrication is concerned, the spiral corrugation wins the race.

Vicente et al [5] used spirally corrugated tubes for investigation on heat transfer characteristics and friction factor in the turbulent region. The experimental observation shows pressure drop penalty with friction factor rise from 20% to 300% and Nusselt number up to 250%. The enhancement of heat transfer coefficient is characterised with the Prandtl number with function of $\mathrm{Nu} \propto Pr^{0.44}$. Vicente et al [5] found that for the $Re < 1000$ the better enhancement of heat transfer is achieved with the higher severity index tube while for $10000 < Re > 40000$ the choice of good tube is with intermediate roughness. Correlation obtained for the heat transfer and pressure drop can be utilized to choose better tube having roughness and helpful replacing plain tube.

San and Huang [6] used transverse ribs for the heat transfer enhancement with parameters shown in Table 1. Result of Nu shows linear variation of Nu with the Re number. Friction factor when correlates with e/d and p/d it shows that influence of e/d is more significant than p/d . Nu was correlated with $Re, p/d$ and e/d . With large number of data Nusselt number and friction factor were correlated with p/d and e/d to plot performance map in the form of efficiency index and heat transfer enhancement index for a given Reynolds number. This map is an indication of both of index parameter for a given value of p/d and e/d of tube.

Bilen et al [7] used circular, rectangular and trapezoidal grooved tube for the enhancement of heat transfer coefficient. The highest enhancement of heat transfer coefficient is obtained at highest $Re = 38000$ and it is for circular groove 63%, trapezoidal groove 58% and rectangular groove 47%. Correlation of heat transfer coefficient and friction factor is obtained with the giver experimental data. Heat transfer coefficient increases with Reynolds number for all the grooved channel.

Pethkool et al [8] used helically corrugation in tube for the enhancement of heat transfer for the turbulent flow. The observations show the higher heat transfer performance than smooth tube. The enhanced performance is in the range of 123% to 232% based on the e/p ratio and Re number. Corrugated tubes gave highest performance of 2.3 times compared with smooth tube. Corrugation also raises the pressure drop penalty with rise in the friction factor in the range of 1.46 to 1.93. Pethkool et al [8] also developed correlation relating Nu nuber with Re number, Pr number, p/d and e/d ratios.

García et al [9] studied and compared three different roughened configuration coil tube, spirally helical corrugation and dimpled surface tube for the enhancement of heat transfer. The result shows use of dimpled and corrugated tube is recommended for the Re number above 2000. For the Re number below 200 use of roughened do not improve much heat transfer compare to smooth tube. Roughened surfaces are not recommended in the laminar regions of flow. It also shows that roughened surfaces causes more influence on pressure drop compare to the heat transfer enhancement.

Aroonrat et al [10] performed experimental study to investigated fluid flow and heat transfer characteristics using internally grooved tubes with parameters as shown in Table1.The result shows enhancement in the heat transfer with pressure drop penalty with grooved tube compared to the plain tube. However there are not significant improvements for the higher pitch of groove. The enhancement of Nu number increases with the Re number and the enhancement increases with decrease in the pitch of the groove. The enchantment factor correlating enhancement of heat transfer and pressure drop penalty is higher than unity for the helical grooved where it was lower than unity for the tube with straight groove.

V. CONCLUSIONS

The present work gives the ready reference on investigation on heat transfer enhancement using corrugated tube. The general observation found is the enhancement of heat transfer with corrugated tube compared to the plain tube. However the heat transfer enhancement is coupled with the pressure drop penalty. It is found that corrugation on the tube will gives suitable enhancement in the turbulent region and not much effective in the laminar region. Heat transfer enhancement and pressure drop penalty increases with increase in the e/p ratio.

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