

Heat transfer enhancement in a pipe using vortex generator

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Abstract— This paper presents the use of a pair of vortex generators to increase the heat transfer coefficient in laminar and turbulent flow inside a circular pipe. A pair of vortex generator with a height of 6 mm and angle of attack of 25° was installed inside a 12 mm diameter pipe. The flow pattern inside the pipe was visualized using dye injection method for the Reynolds number lower than 2100, to ensure the vortex generator produced turbulent flow. Then, the improvement on heat transfer enhancement of this vortex generator was evaluated through experiment. For the flow with Reynolds number less than 2000, the increase in heat transfer coefficient is 10 %. Tests with Reynolds number higher than 5000 did not yielded a conclusive result due to limitation on the heat transfer coefficient on the outer surface of pipe. It is expected that the vortex generator presented in this paper could be used to enhance heat transfer performance in thermoelectric heat pump system.

Keywords— *Vortex generator, heat transfer enhancement, thermoelectric heat pump*

I. INTRODUCTION

The performance of a thermoelectric heat pump is closely related to the heat transfer coefficient between fluid and heat exchange surface. We postulate that a higher heat transfer coefficient will enhance the module's performance. The objective of this paper was to investigate the possibility of heat transfer augmentation in a pipe by an addition of vortex generator at the Reynolds number below 2000 and above 5000. This vortex generator will be used in a thermoelectric heat pump system that operating with a low volume flow (hence at a low Reynolds number) rate of heat transfer fluid.

Several methods could be used to improve the heat transfer performance between a heat exchange surface and fluids. Those methods are flow pattern enhancement, surface treatment, extended surface/fin, and use of nanofluids [1]. Flow pattern enhancement is an obstruction inside a pipe/conduit that will induce fluid mixing (Fig. 1). Flow pattern of fluid will changed from laminar to turbulent after the fluid pass through the vortex generator. The structure that causes obstruction is usually called as vortex generator [2]. For the heat transfers that involve phase change, surface treatment could be beneficial [3]. For instance, rough surface acts as nucleation site in pool boiling. Extended surface/fin

provides an opportunity in increasing the effective heat transfer area by having an additional structure that will be in contact with surrounding fluid [4]. However, a significant increase in the weight of apparatus is not avoidable if a large number of fins are installed. Recent development in nanotechnology yields nano-fluid, a mixture of nano-sized particles and base fluid [5]. However, cost to produce and maintaining homogeneity of nanofluid is relatively high, particularly in applications where low operational cost is important. It can be concluded that vortex generator could improve heat transfer performance of a system deals with a single phase heat transfer, without a significant increase in cost and weight of the thermal system.

In this paper, the flow pattern of water flowing through a pair of vortex generator was visualized using dye injection method. Then, the performance of this vortex generator was tested in a series of experiment in the range of Reynolds number between 1700 and 7000. Comparison between the heat transfer coefficient for a pipe equipped with a pair of vortex generator and a smooth pipe is presented in this paper.

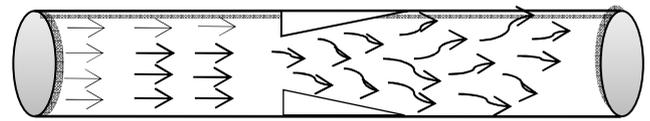


Fig.1: Schematic diagram of a pipe equipped with a pair of vortex generator

II. EXPERIMENT AND THEORETICAL BACKGROUND

This section deals with the visualization of flow pattern inside a pipe, experimental apparatus and procedures and equations to obtain heat transfer coefficient from the experiments and theoretical heat transfer coefficient.

A. Flow visualization

The direct dye injection method was used to visualize the flow pattern inside a transparent pipe (12 mm diameter) equipped with a pair of vortex generator (Fig. 1). The dye was injected using a syringe and needle with an average mass flow rate of 5 ml/minute (Fig. 2). The shape of vortex generator used is as presented in Fig. 3, with the height of 6 mm and

angle of attack of 25°. The range of Reynolds number was between 1700 and 2100, which yields laminar flow inside a smooth pipe before it changed to a turbulent flow after it pass through the vortex generator.



Fig. 2: Dye injection method to make the flow pattern visible

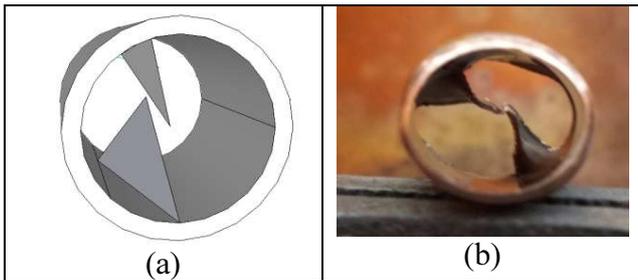


Fig. 3: (a) Schematic of vortex generator and (b) the actual vortex generator inside a 12 mm diameter copper pipe

B. Experiment apparatus and procedures

The experimental set-up (Fig. 4) consists of a hot water tank, a variable speed pump, a constant temperature water bath, a 12 mm diameter smooth copper pipe test section and a 12 mm diameter copper pipe test section equipped with a pair of vortex generator. The length of the test section for both pipes are 1 m. Type K thermocouples were attached inside the hot water tank (T_h), inside the water bath (T_w), at the inlet of smooth pipe ($T_{s,in}$) and pipe with vortex generator ($T_{v,in}$), and at the outlet of smooth pipe ($T_{s,out}$) and pipe with vortex generator ($T_{v,out}$). These temperatures were logged using TC-08 thermocouple logger.

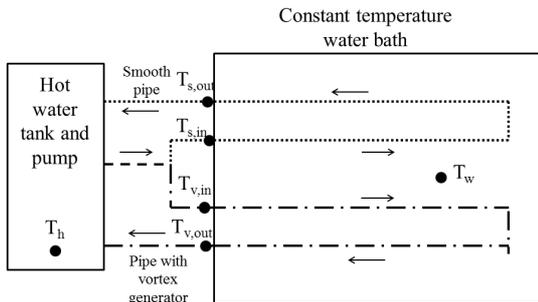


Fig. 4: Apparatus to determine heat transfer coefficient. Black dots indicate the location of Type K thermocouples and the arrows show the direction of fluid flow.

The temperature inside the hot water tank was set to 60°C. Then, the pump was set with the minimum flow rate. The mass flow rate of water was determined by measuring the volume of water flowing through each pipe in a given time. The experiments were carried out until all temperatures reached steady-state. Then, the volume flow rate of the pump was increased. The steps mentioned above were repeated to obtain another set of temperatures.

C. Heat transfer coefficient from experiment

The pipes in test section were cooled by natural convection on it outer side. The Nusselt number (Nu_o) was calculated using [4]

$$Nu_o = 0.60 + \frac{0.387Ra^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}} \quad (1)$$

where Pr is the Prandtl number and Ra is the Rayleigh number. The Prandtl number[4] was calculated by

$$Pr = \frac{\mu c_p}{k} \quad (2)$$

where μ is the dynamic viscosity of water, c_p is the specific heat of water and k is the thermal conductivity of water. The Grashof number[4] was calculated by

$$Gr = \frac{D^3 \rho^2 g \Delta T \beta}{\mu^2} \quad (3)$$

where D is the diameter of the pipe in test section, ρ is the density of water, g is the gravitational constant, ΔT is the temperature difference between pipe surface and cold water bath and β is the thermal expansion coefficient of water.

The external heat transfer coefficient (h_o) was calculated by

$$h_o = \frac{Nu_o k}{D} \quad (4)$$

where h_o was found to be 1250 W/m² K.

Heat transfer resistance through pipe wall[1] is

$$R_{pipe} = \frac{\ln r_o/r_i}{2\pi k L} \quad (5)$$

where r_o is the internal radius of pipe, r_i is the inner radius of pipe and k is the thermal conductivity of pipe and L is the length of pipe in test section.

The average internal heat transfer coefficient (h_i) obtained through experiment was calculated by

$$Q = \frac{\Delta T_{lm}}{\frac{1}{h_o A_o} + \frac{\ln r_o/r_i}{2\pi k L} + \frac{1}{h_i A_i}} = \dot{m} c_p (T_{in} - T_{out}) \quad (7)$$

where ΔT_{lm} is the log mean temperature difference between pipe and water in the water bath, \dot{m} is the mass flow rate of water flowing through the test pipe, c_p is the specific heat of water, and T_{in} and T_{out} are the inlet and outlet for smooth pipe or pipe with vortex generator.

D. Theoretical heat transfer coefficient

For the internal heat transfer coefficient, two possible scenarios are considered. Those scenarios are fully developed laminar flow and the developing laminar flow. For the fully developed laminar flow with constant wall temperature, the Nusselt number is 3.66[4].

To get a more realistic estimation of heat transfer coefficient, the developing laminar flow heat transfer correlation[4] was used

$$Nu_i = 7.54 + \frac{0.03 \left(\frac{D_h}{L}\right) Re Pr}{1 + 0.016 \left[\left(\frac{D_h}{L}\right) Re Pr\right]^{2/3}} \quad (8)$$

where Re is the Reynolds number, D_h is the hydraulic diameter (equivalent to internal diameter for a circular pipe) of the pipe and L is the length of pipe.

For a fully developed turbulent flow region, Dittus-Boelter equation[1] was used (Equation 9).

$$Nu_i = 0.023 Re^{0.8} Pr^{0.3} \quad (9)$$

The Reynolds number is

$$Re = \frac{\rho u D}{\mu} \quad (10)$$

The internal heat transfer coefficient (h_i) can be calculated using

$$h_i = \frac{Nu_i k}{D} \quad (11)$$

III. RESULTS

A. Flow visualization

Fig. 5 shows the flow pattern of water immediately after it flows through the vortex generator. The intensity of turbulent eddies increases as the Reynolds number increases. These diagrams show that the vortex generator was able to create turbulent flow at the Reynolds number lower than the 2300, where laminar flow is expected for a flow inside a smooth pipe. To date, we are developing an automated image analysis method to quantify the size of these eddies.

B. Internal heat transfer coefficient

In Figure 6, heat transfer coefficients that were obtained through theoretical and experimental methods are presented. The heat transfer coefficient for the pipe with vortex generator is higher than the heat transfer coefficient of a smooth pipe although the Reynolds number for the flow inside the pipe with a vortex generator is lower. Figure 6(b) shows that the heat transfer coefficient for the pipe with vortex generator is about 10 % higher compared to the smooth pipe although the Reynolds number is 5% lower (for the smooth pipe).

For the laminar flow region, the developing laminar flow theory fits better the experimental results. This may be due to the nature of pipe in the test section that has bends, which make the flow is continuously in the developing laminar flow characteristic.

It also can be seen that for the turbulent region, the heat transfer coefficient through experiment is much lower compared to the heat transfer coefficient predicted using Equation 10. This may be due to limitation on the heat transfer coefficient at the outside surface of pipe. The calculated heat transfer coefficient was 1250 W/m²K.

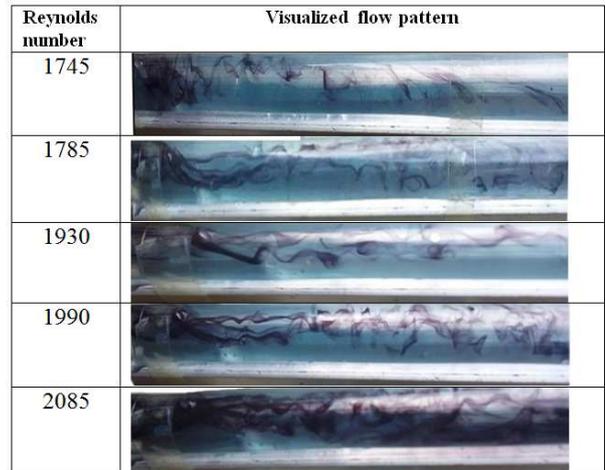


Fig. 5: Flow pattern at various Reynolds number. The inner diameter of the pipe is 12 mm

IV. DISCUSSION

Several improvements on the experiment apparatus can be implemented in the future. Heat transfer at the external surface of test pipe can be increased by inducing forced convection or applying phase change heat transfer method. Alternatively, the pipe wall can be maintained at a constant temperature by applying an electrical resistance heater. The measurement of pressure drop along the test section will enable the calculation of Performance Evaluation Criteria of this vortex generator.

The technique of flow visualisation pattern could be automated, in term of dye injection and image analysis. A constant speed of plunger movement will enable a constant

mass flow rate of dye introduced into the pipe. For the image analysis, we are developing an automated method to quantify the intensity of eddy in the pipe.

It was our intention to integrate the results obtained in this paper with our work on thermoelectric heat pump. A transient heat transfer model on thermoelectric heat pump system is partially completed at the time of writing.

V. CONCLUSION

A heat transfer enhancement in a circular pipe using a pair of vortex generator was studied. It can be concluded that the 10% increase in heat transfer coefficient could be achieved in the laminar flow region. It was found that the external heat transfer coefficient lead to the lower internal heat transfer coefficient relative to the theoretical estimation in turbulent flow region. Future work will explore the possibility of integrating this vortex generator with our work on the thermoelectric heat pump system.

Acknowledgment

Authors would like to acknowledge financial assistance from Universiti Kuala Lumpur under the Final Year Project and Conference Grant scheme.

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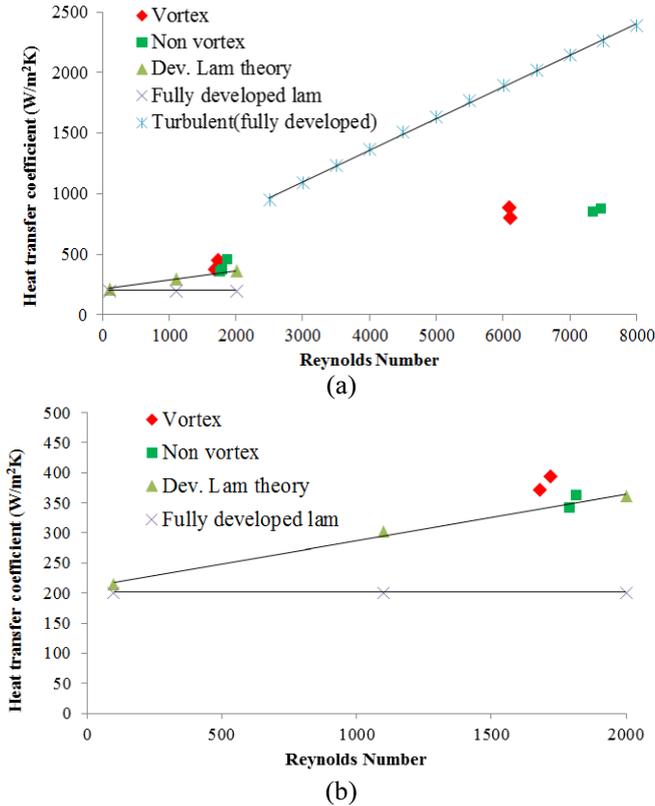


Figure 6: (a) The comparison of heat transfer coefficient between the theoretical, pipe with vortex and smooth pipe, and (b) Enlarged view of laminar flow region.