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# Heat Transfer from a Cylinder in Cross-Flow of Single and Multiphase Flows

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***Abstract*—**In this paper, the average heat transfer characteristics for a cross flow cylinder of 16 mm diameter in a vertical pipe has been studied for single-phase flow (water/oil) and multicomponent (non-boiling) flow (water-air, water-oil, oil-air and water-oil-air). The cylinder is uniformly heated by electrical heater placed at the centre of the element. The results show that the values of average heat transfer coefficients for water are around four times the values for oil flow. Introducing air as a second phase with water has very little effect on heat transfer rate, while the heat transfer increased by 70% in case of oil. For water–oil flow, the heat transfer coefficient values are reflecting the percentage of water up to 50%, but increasing the water more than 50% leads to a sharp increase in the heat transfer coefficients to become close to the values of pure water. The enhancement of heat transfer by mixing two phases may be attributed to the changes in flow structure near to cylinder surface which lead to thinner boundary layer and higher turbulence. For three-phase flow, the heat transfer coefficients for all cases fall within the limit of single-phase flow of water and oil and are very close to pure water values. The net effect of the turbulence augmentation due to the introduction of air and the attenuation due to the introduction of oil leads to a thinner boundary layer of oil over the cylinder surface covered by a mixture of water and air bubbles.

***Keywords*—**Circular cylinder, cross-flow, heat transfer, multicomponent multiphase flow

## NOMENCLATURE

| | |
|---|---|
| $A_o$ | The outer surface area of the supporting insulating cylinders |
| $A$ | Area of heated cylinder (m$^2$) |
| $C$ | Specific heat of steel (J/kg ºC) |
| D | Pipe diameter |
| $d_i$ | Inner cylinder diameter |
| $d_o$ | Outer cylinder diameter |
| $h$ | Surface heat transfer coefficient (W/m$^2$ K) |
| $K$ | Thermal conductivity of steel (44 W/m K) |
| $m$ | Mass of cylinder (kg.) |
| $Nu$ | Nusselt number (hd/$K_f$) |
| $Nu_{av}$ | Average Nusselt number |
| $q_{loss}$ | The heat loss from the insulating cylinders |
| $q_{conv}$ | The convective heat loss from the cylinder surface, |
| $Re$ | Reynolds number |
| $t$ | Time (s) |
| $T$ | Temperature of cylinder surfaces at any time |
| $T_f$ | Free stream fluid temperature |
| $T_i$ | Temperature of cylinder inner surface |
| $To$ | Initial temperature of cylinder surface |
| $T_s$ | Cylinder surface temperature |
| $U_o$ | The overall heat transfer coefficient |
| $u$ | Velocity (m/s) |
| x, y, z | Cartesian coordinates (m) |

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## I. INTRODUCTION

THE heat transfer and flow characteristics around a cylinder in cross flow are important in several applications such as heat exchangers, hot wire anemometer, nuclear reactor fuel rods, cooling towers, offshore risers, sensors, and probes. The flow could be single-phase, multiphase (boiling), or multiphase (mixture of fluids) depending on the engineering applications. The heat transfer from a smooth cylinder in single-phase flow which was studied by many researchers was reviewed in detail by [1]-[4]. Various variables influencing the heat transfer are considered in these papers, for example: fluid physical properties, flow regime, cylindrical shape, and blockage, turbulence in free stream, thermal boundary conditions, single-phase and boiling flows. The most recent review paper on single-phase flow by [4] which covered a wide range of Reynolds (Re) and Prandtl (Pr) numbers summarised the most widely used empirical correlations for estimation of heat transfer from a hot cylinder to a single-phase flow. These empirical correlations are used to validate the present experimental measurements for single-phase flow. A summary of the relevant papers found in literature on heat transfer from a heated cylinder to a multiphase flow is given hereafter.

References [5], [6] investigated the heat transfer from a hot cylinder of 37.5 mm diameter in cross flow of water-air mixture. They investigated the effect of water/air mass ratio and Re on the overall and local heat transfer coefficient in turbulent air flow. The heat transfer was very sensitive to the quantity of water in flow of mixture which is more than 10 times greater than the single-phase flow of air. Reference [7] studied the gas phase effect on temperature distribution and average heat transfer coefficient in the flow of coolant (water) in power plants. They used a complicated geometry of triangular shape with curved sides for the channel in cross flow. The results indicated that heat transfer increased significantly at low Re and decreased as Re increased.

References [4], [8] used different fluids with Pr in the range of 0.7 to 176 to study the heat transfer from cylinder in cross flow experimentally. Three different flow patterns of laminar, reattachment, and periodic vortex flow were identified. Empirical formula was given to calculate Nusselt (Nu) from Re number and Pr number. Reference [9] studied the heat transfer from a cylinder in cross flow of water and oil. They found that the heat transfer for water is increased about 2~3 times that of oil for the same superficial velocity.

The main purpose of this paper is to study the heat transfer from a heated cylinder in cross flow of mixture of fluids, which has received relatively little attention. A major difference between the present work and the large number of published papers in literature is the use of mixture of different fluids instead of boiling fluid. The measurements are carried out for single-phase flow to validate the present measurements with data from literature. The heat transfer data for water and oil are also used as a reference for multiphase flow measurements. The effect of introducing air is studied by collecting data for water-air, oil-air, and water-oil-air mixtures.

## II. Experimental Facility and Instrumentation

Fig. 1 shows schematic diagram of experimental facility used in the present investigation. The water and kerosene are supplied from the separation/storage tank where the mixture returns from the test section to the separates. Pure water and oil were are pumped from the bottom of the tanks to the mixing chamber by two pumps through two flow meters for water and oil. The air is supplied from the air compressor through the air flow meter to the mixing chamber. The mixture leaves the test section to the separation tank via the return flow pipe. The test section which is 3500 mm long with 77.8 mm inner diameter gives a developing length of L/D=44. The flow meters of the three phases are connected to the computer which logged, stored, and displayed the flow rates.

The heated cylinder of 16 mm outer diameter is mounted horizontally in the vertical pipe. The heated cylinder where the heat is generated and transferred to the fluid supported from both sides by two cylinders of 16 mm diameter made of insulating material. The heated cylinder made of steel with 6 mm inner diameter, 16 mm outer diameter, and 10 mm length. Three PT100 temperature sensors are used to measure the outer surface temperatures at three location 90$^o$ apart from each other at the stagnation point, the side and rear of the cylinder.

The heat is provided by electrical heater placed at the centre of the middle section which can be controlled by changing the input voltage. The fluid temperature was also measured by a PT100 sensor inserted in the flow upstream the cylinder. The temperatures were monitored to reach steady state condition before the temperatures was recorded.

TABLE I
Flow Conditions (D: Pipe Diameter, d: Cylinder Diameter)

| Velocity (m/s) | Water ($Re_D$) | Water ($Re_d$) | Oil ($Re_D$) | Oil ($Re_d$) |
|---|---|---|---|---|
| 0.233 | 11297 | 2442 | 832 | 179 |
| 0.35 | 16970 | 3669 | 1249 | 270 |
| 0.58 | 28121 | 6080 | 2070 | 447 |
| 0.814 | 39466 | 8533 | 2906 | 628 |
| 0.93 | 45090 | 9749 | 3320 | 717 |

Steady state approach was used for both water and oil single-phase flow as the temperature difference between the cylinder and the fluid was less than 10 $^o$C. The flow conditions used for single-phase flow are given in Table I.

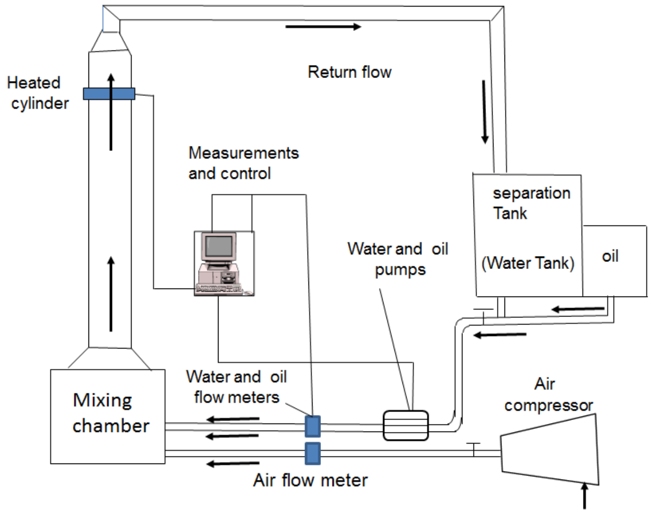


Fig. 1 Schematic diagram of experimental facility

## III. Analysis of Experimental Data

The heat transfer coefficient $h_o$ is calculated under the steady condition for heat flux, $q$= 9225 W/m$^2$ as:

$$h_o = \frac{q_{conv}}{(T_s - T_f)} = \frac{q - q_{loss}}{(T_s - T_f)} \tag{1}$$

where $q_{conv}$ is the heat transfer from the cylinder surface, $q_{loss}$ is the heat loss from the supporting cylinders, $T_s$ is the cylinder surface temperature, and $T_f$ is the free stream fluid temperature.

The heat loss through the supporting cylinders was estimated as:

$$q_{loss} = U_0 A_0 (T_i - T_f) \tag{2}$$

where $U_o$ is the overall heat transfer coefficient, $A_o$ is the outer surface area of the supporting insulating cylinders, and $T_i$ is the inner surface temperature of the supporting cylinders. The overall heat transfer coefficient through the insulating cylinders

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{x_w}{k_w}\frac{d_o}{d_w} \tag{3}$$

where $h_o$ is the heat transfer coefficient from the outer surface of the supporting insulating cylinders, $x_w$ is the thickness of the cylinder wall, $k_w$ is the thermal conductivity of the insulating material, and the insulation mean diameter can be calculated as

$$d_w = \frac{d_o - d_i}{\ln(d_o / d_i)} \quad (4)$$

where $d_i$ and $d_o$ are the inner and outer diameters of the cylinders, respectively.

The inside temperature is estimated from the measured outer surface temperature of the heated cylinder. The outside heat transfer coefficient used in (3) is calculated by assuming that all the heat is transferred to the fluid through the heated cylinder. The calculation shows that the losses are about 9% for water flow and 25% for oil flow. Then, the heat fluxes used to calculate the experimental heat transfer coefficients for water and oil flows are adjusted to be 8500 W/m$^2$ and 7100 W/m$^2$, respectively.

## IV. Results and Discussion

### A. Single-Phase Flow

The single-phase flow measurements are carried out in order to check the accuracy of the instrumentation and to verify the consistency of the present data with the data from literature and to produce the reference values of heat transfer coefficients for water and oil to be used for comparison with multiphase flow measurements. Fig. 2 compares the Nu of water flow from the present work with the correlations of [8], [10]. The present experimental measurements are within the range of estimated Nu values from the correlations given in literature. Fig. 3 compares the Nu of oil flow from the present work with the correlations of [9], [11] which compared well with the previous work from literature.

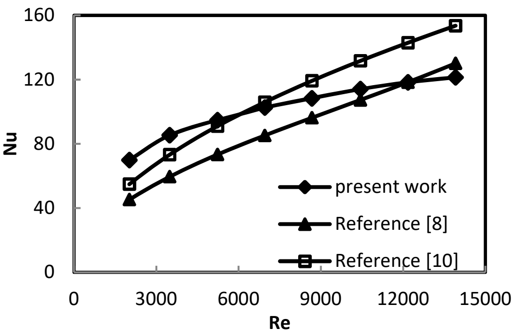


Fig. 2 Comparison of Nu from the present work with data from literature (water)

### B. Water–Air and Oil-Air Two-Phase Flow

Figs. 4 and 5 present the variation of heat transfer for water-air and oil-air two-phase flows. For water-air flow, it can be observed that the water has a dominant effect on heat transfer coefficient as the values are very close to the values of pure water. For oil-air flow, the heat transfer coefficient values are about 1.7 times the values of pure oil. These results are significantly different from the case of water-air flow. The different behaviour may be attributed to the type of flow upstream for the heated element. The data in Table I show that the flow of water is turbulent as the Re numbers based on pipe diameter are in the range of 11300-45000. In contrast, the flow of oil can be considered laminar as the Re numbers are in the range of 800-3300. In general, the high heat transfer coefficient in two-phase flow compared to single-phase flow can be explained as:

- Introducing the second phase (bubbles/drops) increases the turbulence near the heated wall due to the wake behind the bubbles. The additional turbulence reduces the boundary layer thickness which causes the major resistance to heat transfer. This could explain the more pronounced effect on oil-air (laminar flow of oil) compared to water-air flow (turbulent flow of water). The two-phase flow turbulence was studied by [12]-[14]. They found that turbulence increased significantly when a small amount of air was introduced into the single-phase flow, and that any additional amounts had a small effect. They also observed that the discrepancy between the two-phase flow and single phase turbulence decreases with higher liquid velocities.
- The increase in turbulence upstream the heated cylinder. The effect of main stream turbulence on heat transfer coefficient from the cylinder surface was studied by [3], [15] for single-phase flow. They found that local heat transfer coefficient increased by 30-50% as the free stream turbulence intensity increased from 0.8 to 7.8%. This effect was strongest in the front part of the cylinder and becomes less pronounced with angular distance. In the present work, the difference in heat transfer behaviour by introducing air to water (turbulent) and to oil (laminar) may be partially attributed to a signification increase in turbulence in case of oil compared to water.
- The flow pattern of multiphase flow: The flow pattern in the main stream depends on flow rates, the physical properties of fluids, and the pipe inclination [13], [16]-[18]. The two-phase flow around obstacles was also studied experimentally by [19], [20]. They found that: i) In the region directly behind the cylinder, a strong vortex of the liquid combined with the accumulation of gas was observed; ii) At the stagnation point and both the sides of the cylinder, a zone with lower gas content close to the cylinder surface was appeared.

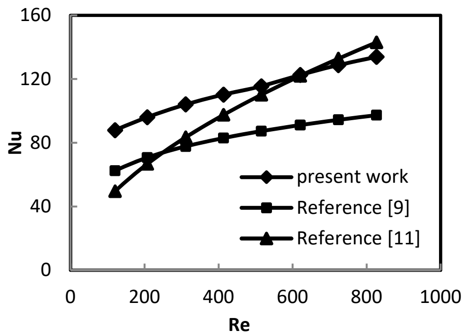


Fig. 3 Comparison of Nu from present work with data from literature (oil)

In summary, the combined effect of turbulence modification and changes in flow pattern in the stagnation zone in front of the cylinder influence the local and the average heat transfer coefficient for the cases of water-air and oil-air mixtures.

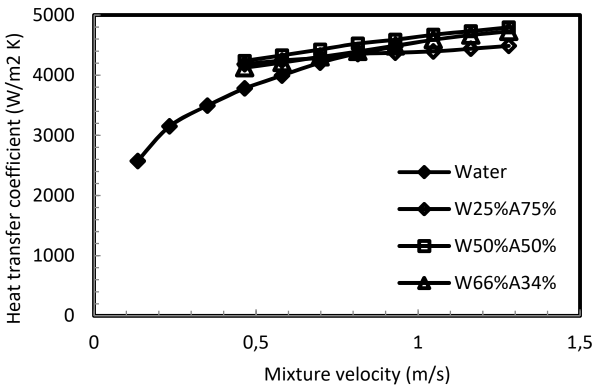


Fig. 4 Variation of average heat transfer coefficient with mixture velocity of water-air two-phase flow

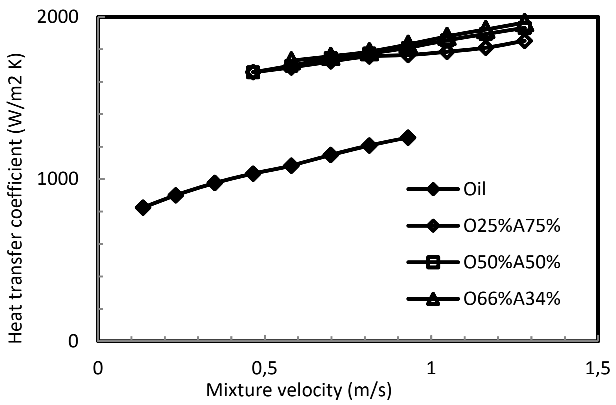


Fig. 5 Variation of average heat transfer coefficient with mixture velocity of oil-air two-phase flow

*C. Water-Oil Two-Phase Flow*

Fig. 6 presents the variation of average heat transfer coefficient with mixture velocity of water-oil two-phase flows. The results show that heat transfer coefficient is a function of volumetric quality which is different from the cases of water-air and oil-air mixtures. This can be attributed to lower kerosene drop velocity compared to air bubble velocity. The low drop velocity creates less wake turbulence that affected the boundary layer thickness on the cylinder surface. For the cases of W25%O75% and W50%O50%, the change in heat transfer coefficient is a reflection of the change in oil volumetric quality. This is an indication that the majority of the cylinder surface is covered by a layer of oil forming the boundary layer due to its higher viscosity compared to the water. This may be attributed to the additional turbulence generated due to the water drops which reduce the oil boundary layer and enhance the heat transfer coefficient to become higher than the pure oil values. For the case of W75%O25%, the effect of oil drops on heat transfer coefficient is very much similar to effect of air bubbles in air-water flow which was explained in the previous section.

To the best of our knowledge, there is no published data in literature which can be used to verify or support the present work on heat transfer from a heated cylinder in cross flow of liquid-liquid mixture. However, [21] carried out a similar study on the heat transfer of water-diesel two-phase flow in a shell side of a shell and tube heat exchanger. They observed that the heat transfer coefficients for water-diesel mixtures fall within the boundaries of the pure water and pure oil data. These results support the present finding in spite of the significant difference between the two geometries.

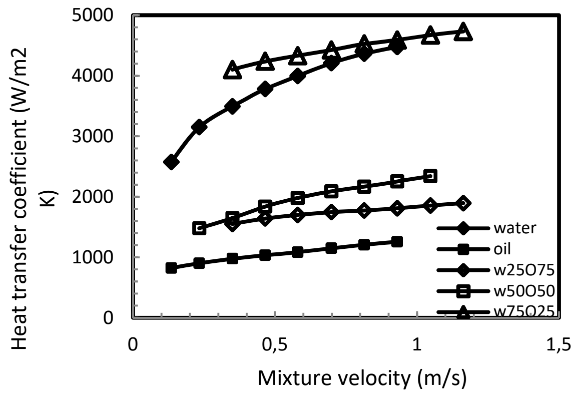


Fig. 6 Variation of average heat transfer coefficient with mixture velocity of water-oil two-phase flow

*D. Water–Oil-Air Multiphase Flow*

Fig. 7 presents the variation of heat transfer coefficients for water-oil-air three-phase flow with the mixture velocities. The heat transfer coefficients are influenced by the hydrodynamic of the flow and the properties of the fluids. The heat transfer coefficients for all of the different mixtures fall within the range of the pure water and oil data. Based on two-phase flow cases, the introduction of air leads to augmentation of turbulence but introducing oil leads to attenuation of the turbulence. The combined effect of the augmentation and attenuation of turbulence creates a thin boundary layer of oil over the cylinder surface covered by a mixture of water and air bubbles.

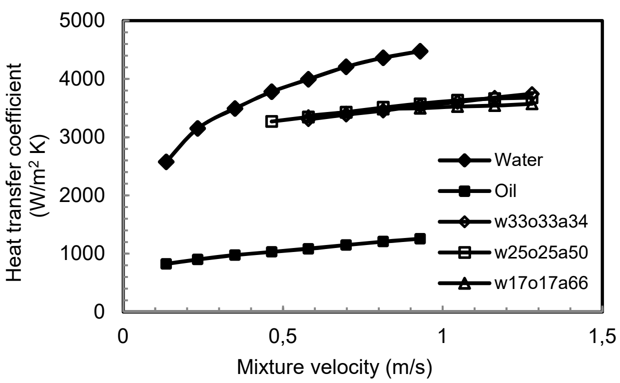


Fig. 7 Variation of heat transfer coefficients for water-oil-air three-phase flow with mixture velocity

## V. Conclusions

Heat transfer from a heated circular cylinder to a single-phase and multiphase flows have been investigated using water, oil, and air as single-phase flows and a combination of two or three of them as multiphase flow.

- For single-phase flow, the results show that the average heat transfer coefficients for water are about four times the heat transfer coefficient of oil.
- The average Nu numbers for single-phase flow of water and oil are in reasonable agreement with the previous work from literature.
- Introducing air as second phase with water has no effect on the heat transfer coefficients of pure water.
- Introducing air as second phase with oil enhances the heat transfer coefficient significantly, and it becomes higher than that for pure oil flow. The enhancement in heat transfer is due to a reduction in boundary layer thickness, an increase in turbulence the main stream.
- For water–oil mixture, the heat transfer coefficient is close to oil for high volumetric quality (≥ 50%) but increased significantly for low oil volumetric quality (25%) which becomes even higher than water single-phase flow.
- For water, oil and air mixture, the heat transfer coefficients for all mixtures fall within the boundaries of the pure water and oil data. This can be attributed to the net effect of the augmentation due to air and the attenuation due to oil of turbulence.

## References

[1] Zukauskas, A. A., 1972, Heat transfer from tubes in cross-flow, Adv. Heat Transfer 8, 93–160.
[2] Morgan, V. T., 1975, The overall convective heat transfer from smooth circular cylinders, Adv. Heat Transfer 11. 199-264.
[3] Zukauskas, A. A., Ziugzda, J., 1985, Heat transfer of a cylinder in cross-flow, Hemisphere Publishing Corporation,
[4] Sanitjai, S., Goldstein, R.J., 2004a, Forced convection heat transfer from a circular cylinder in cross-flow to air and liquids, Int. J. Heat Mass Transfer 47, 4785-4794.
[5] Hoelscher, J. F., 1965, study of heat transfer from heated cylinder in two-phase flow, water-air flow, MSc thesis, Air Force Institute of Technology, Ohio.
[6] Takahara, E. W., 1966, Experimental study of heat transfer from a heated circular cylinder in two-phase, water-air flow, MSc thesis, Air Force Institute of Technology, Ohio.
[7] V. P. Bobkov, V. F. Sinyavskii, and N. K. Savanin, Effect of gas phase on heat transfer in turbulent water flow in a model of compact triangular rod bundle, Translated from Inzhenerno-Fizicheskie Zhurnal 44 (1972), pp.362-367.
[8] Sanitjai, S., Goldstein, R.J., 2004b, Heat transfer from a circular cylinder to mixtures of water and ethylene glycol, Int. J. Heat Mass Transfer 47, 4795-4805.
[9] Hu, Z., Yang Y., Zhou, F., 2005, Study on the heat transfer of cross flow in vertical upward tubes, Journal of Zhejiang University Science 24, 1128-1131.
[10] Fand, R. M., 1965, Heat transfer by forced convection from a cylinder to water in cross-flow. Int. J. Heat Mass Transfer 8, 995–1010.
[11] Whitaker, S., 1972, Forced convection heat transfer calculations for flow in pipes, past flat plate, single cylinder, and for flow in packed beds and tube bundles. AIChE Journal 18, 361–371.
[12] Theofanous T. G., Sullivan, J., 1982, Turbulence in two-phase dispersed flows", J. Fluid Mechanics 116, 343-362.
[13] Wang, S. K., Lee, S. J., Jones, O. C., Lahey, R.T., 1987, 3-D turbulence structure and phase distribution measurements in bubbly two-phase flows", Int. J. Multiphase Flow 13, 327-343.
[14] Shawkat, M. E., Ching, C. Y., Shoukri, M., 2007, On the liquid turbulence energy spectra in two-phase bubbly flow in a large diameter vertical pipe, Int. J. Multiphase Flow 33, 300-316.
[15] Ghisalberti, L., Kondjoyan, A., 1999, Convective heat transfer coefficients between air flow and a short cylinder. Effect of air velocity and turbulence, effect of body shape, dimensions and position in the flow, Journal of Food Engineering 42, 33-44.
[16] Liu T. J., Bankoff, S.G., 1993, Structure of air-water bubbly flow in vertical pipe-II. void fraction, bubble velocity, and bubble size distribution", Int. J. Heat and Mass Transfer 36, 1061-1072.
[17] Zhao, D., Guo, L., Hu, X., Zhang, X., Wang, X, 2006, Experimental study on local characteristics of oil-water dispersed flow in a vertical pipe", Int. J. Multiphase Flow 32, 1254-1268.
[18] Hamad, F. H., Dlir A., Ganesan, P. B., 2014, Study of kerosene-water two-phase flow characteristics in vertical and inclined pipes, Can. J. Chem Eng, 92, 905-917.
[19] Krepper, E., Beyer, M., Frank, T., Lucas, D., Prasser, H., 2009, CFD modelling of polydispersed bubbly two-phase flow around an obstacle, Nuclear Engineering and Design 239, 2372–2381.
[20] Habeeb, L. J., Al-Turaihi, R. S., 2013, Experimental study and CFD simulation of two-phase flow around multi-shape obstacles in enlarging channel, American Journal of Mechanical Engineering 1, 470-486
[21] Alagesan V., Sundaram, S., 2012, Two-phase experimental heat transfer studies on a water-diesel system in a shell and tube heat exchanger 29, 275-283.