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Study of effects of rotational rate of a cylinder on the film boiling phenomenon of water undergoing phase change over two heated cylinders in tandem arrangement

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ABSTRACT*: The problems of fluid flow and heat transfer phenomena over an array of cylinders are quite prominent in fluid dynamics and industry applications. These problems give rise to some of the important aspects in fluid dynamics theory such as fluid flow interaction, interferences in flow, vortex dynamics and a variety of engineering applications such as compact heat exchangers, cooling of electronic equipment, nuclear reactor fuel rods, cooling towers, chimney stacks, offshore structures, hot-wire anemometry and flow control. The mentioned structures are subjected to air or water flows and therefore, experience flow induced forces which can lead to their failure over a long period of time. Basically, with respect to the free stream direction, the configuration of two cylinders can be classified as tandem, side-by-side and staggered arrangements. The Reynolds Averaged Navier-Stokes (RANS) equations are used to compute the flow. The validation of the results was done with that of the literature. Some of the key predictions such as the coefficient of pressure, magnitude of vorticity, Prandtl number(Pr) and turbulent kinetic energy are presented as a part of the outcome of the research. There is a significant influence of rotation of a cylinder on the film boiling phenomenon that begins from the surface of a heated cylinder. The formation of a new thermodynamic phase, its growth and decay were studied, and it was found that the rate of rotation of the cylinder contributes to better convective heat transfer near the solid surface, and hence, an almost 30% increase of volume of fraction of steam was observed. The evaporation-condensation model was used to establish the interaction between the two phases.*

KEY WORDS*: Phase Change, Film Boiling, RANS, k-ε Turbulence Model, Heat Flux, Rotation*

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I. INTRODUCTION

The problems of fluid flow and heat transfer phenomena over an array of cylinders are quite prominent in fluid dynamics and industry applications, Zdravkovich [1]. These problems give rise to some of the important aspects in fluid dynamics theory such as fluid flow interaction, interferences in flow, vortex dynamics and a variety of engineering applications such as compact heat exchangers, cooling of electronic equipment, nuclear reactor fuel rods, cooling towers, chimney stacks, offshore structures, hot-wire anemometry and flow control. The mentioned structures are subjected to air or water flows and therefore, experience flow induced forces which can lead to their failure over a long period of time. Basically, with respect to the free stream direction, the configuration of the two cylinders can be classified as tandem, side-by-side and staggered arrangements.

Quite a few studies on these problems have been carried out analytically, experimentally, and numerically, especially under the configuration of two tandem cylinders for simplicity. Some of the outstanding research activities in the field have focused on the effect of spacing between the cylinders on the flow characteristics and heat transfer around them. It is observed, therefore, that the nature of the flow relies upon the arrangement of the cylinders [1,2,3]. Numerical simulations of flow over a pair of circular cylinders have been carried out by applying different methods that are mainly based on finite element formulation. Mittal et al. [2] investigated the problem numerically using a stabilized finite element method and reported their study for the Reynolds numbers of 100 and 1000 in tandem and staggered arrangements for different spacings and concluded that at Re = 1000 and L / D = 2.5, the shear layers caused instability due to the increased velocity of flow, unlike Re =100, in which the flow converged to an initial steady state after some transience. Increasing the gap to L / D = 5.5, the flow at Re = 100 showed unsteady behavior. It was observed that the Strouhal numbers that are associated with the vortex shedding of the twin cylinders could take on the same value. The fluid flow over a single cylinder has been amply covered by many articles in the past, and hence, this has motivated us to take up a situation where there is more than one cylinder. Before taking up the problem where a two-cylinder arrangement is considered, it was our belief that the approach and essence of this research would be incomplete without solving flow over a single cylinder. The finding of the research includes the effect of heat on the flows around a single cylinder and around the two-cylinder arrangement. The understanding of film boiling phenomenon during the phase of water flowing over two heated circular cylinders in tandem arrangement is quite complex, and it has a direct impact on the formation vapor when the transfer of mass, momentum and heat happens from the solid surface(cylinder) to bulk liquid(water). The rotation of the cylinder (either one or both) has also direct influence on the phase change occurrence.

The objective is to address all the gaps mentioned above and bring clarity to the complexities and challenges of phase change of water flowing over two heated circular cylinders in tandem arrangement. The specific problem is to assess how the phase change process gets affected by the film boiling when the two phases interact and also to what could be the possible causes of variation volume fraction of water (liquid phase) and steam (vapor phase) when a flow is laminar and turbulent. The formation of a new thermodynamic phase, its growth and decay have been studied, and it has been found that the rate of rotation of the cylinder contributes to enhanced convective heat transfer near the solid surface; an almost 30% increase of volume of fraction(VOF) of steam was noted.

A comparison of VOFs of steam was made between the case when cylinders rotate and the case when the same cylinders are stationary. The evaporation-condensation model was used to establish the interaction between the two.

II. GOVERNING FLOW EQUATIONS

The mass, momentum, and energy conservation equations of the time-averaged equations can be written in a conservative form as follows:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \qquad (1)$$

Momentum conservation equation:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial (\rho u_i u_j + p\delta_{ij})}{\partial x_j} = \frac{\partial (\tau_{ij} - \rho \overline{u_i u_j})}{\partial x_j} \qquad (2)$$

Energy conservation equation:

$$\frac{\partial (\rho e_o)}{\partial t} + \frac{\partial (\rho e_o u_i + p u_i)}{\partial x_i} = \frac{\partial (\tau_{ij} u_j - \rho \overline{u_i u_j} u_j)}{\partial x_i} - \frac{\partial (q_i + C_p \rho \overline{u_i \theta})}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\left(\mu_l + \frac{\mu_i}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]$$

Turbulence Models

In the case of the Reynolds Averaged Navier-Stokes (RANS) equations, a Standard Turbulence Model (STM) such as the two-equation (k-ε) turbulence model is used:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho u_j k}{\partial x_j} = -\rho \overline{u_j u_i}\frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\mu_l + \frac{C_\mu k^2}{\overline{\sigma_k}\varepsilon}\right)\frac{\partial k}{\partial x_j}\right] - \rho\varepsilon(1 + M_\tau^2) \quad (4)$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial \rho u_j \varepsilon}{\partial x_j} = -C_{\varepsilon 1}\rho \overline{u_j u_i}\frac{\partial u_i}{\partial x_j}\frac{\varepsilon}{k} + \frac{\partial}{\partial x_j}\left[\left(\mu_l + \frac{C_\mu k^2}{\overline{\sigma_k}\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - f_2 \rho \overline{C_{\varepsilon 2}}\frac{\varepsilon}{k}\left[\varepsilon - v_l\left(\frac{\partial \sqrt{k}}{\partial n}\right)^2\right] (5)$$

where

$C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $\overline{\sigma_k} = \sigma_k = 1.4$, $\overline{\sigma_\varepsilon} = \sigma_\varepsilon = 1$ and $\overline{C_{\varepsilon 2}} = C_{\varepsilon 2} = 1.92$

$$f_\mu = \exp\left[\frac{-3.41}{\left(1 + \frac{R_T}{50}\right)^2}\right]; \quad R_T = \frac{k^2}{\mu_t \varepsilon}; \quad f_2 = 1 - 0.3\exp(R_T^2)$$

Boundary conditions for epsilon (ε) and k at the wall are

$$\varepsilon_{wall} = \nu_l \left(\frac{\partial\sqrt{k}}{\partial n}\right)^2 ; \; k_{wall} = 0$$

The turbulent stress components are

$$\rho\overline{u_j u_i} = 2\rho\nu_t S_{ji} - \frac{2}{3}\delta_{ji}\rho k$$ and

$$S_{ji} = \frac{1}{2}\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right] - \frac{1}{3}\delta_{ji}\frac{\partial u_j}{\partial x_i}$$

III. METHODOLOGY

The specific problem is to assess how the phase change process gets affected when film boiling happens and simultaneously cylinder(s) rotates and what could be the possible causes of variation of volume fraction of water (liquid phase) and steam (vapor phase) when a flow is stagnant and is in motion. The main focus of the would be to propose a suitable strategy through numerical simulation to use the heat of the cylinders and to observe the wake dynamics as well while the phase change is in process. The situations of fluid flow and heat transfer across an array of cylinders have been quite common in fluid dynamics, and particularly, in industry applications. One such situation is the flow of water over heated cylinders arranged in tandem arrangement . The available experimental investigations and numerical simulations have been referred for validation purposes. Hence, prior to focusing on the results, validation has been done with respect to complex flow parameters such as the drag forces, pressure distribution, velocity profile, vortex shedding frequency, Nusselt number, Strouhal number and flow patterns. The following methodology is adopted to carry out the research work. The continuity, momentum and energy equations are solved for the flow over two cylinders. A sketch definition of numerical set-up (shown in x-y plane) for two circular cylinders in tandem arrangement with boundary conditions is shown in Fig.1. The necessary dimensions of the fluid domain are expressed in terms of the diameter (D) of a cylinder. The diameters of both the cylinders are the same. The components of velocity (U) are u and v in x-, y-directions respectively. T is the temperature which has free stream value at the inlet of the flow(left to right in the flow domain), and it is equal to the wall temperature specified at the boundary of the solid surfaces of the both the cylinders. The results are presented after validating the code with NASA experimental results and the influence on the phase change and wake dynamics.

The validation for a flow over a single circular cylinder (with and without heat flux) is extensively done, and then the validation of the flow over two circular cylinders is carried out with a literature wherein experimental results are published for rotating and non-rotating cylinders with varied heat flux.

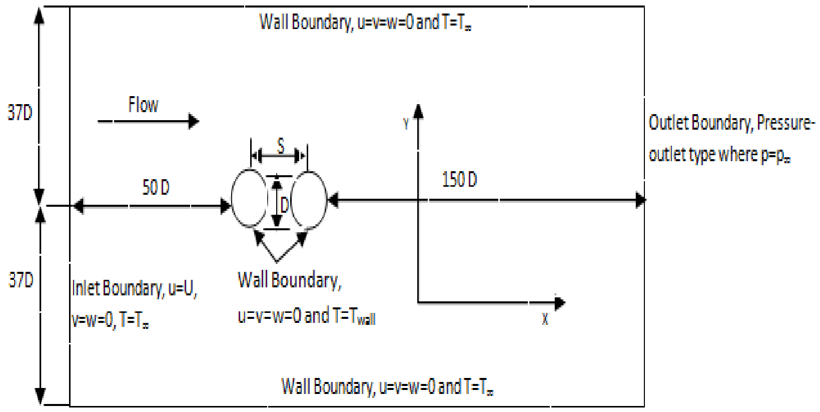

Fig. 1: Sketch definition of numerical set-up (shown in x-y plane) for two circular cylinders in tandem arrangement with boundary conditions

To solve the problem defined above commercially available CFD (computational fluid dynamics) solver, Ansys(R)Fluent 12.0 has been used.

Convergence and mesh independence study

The convergence of the numerical solutions obtained from the above-mentioned problem is obtained by the residuals of the values of variables. In this work, convergence occurs when the values of the total residual become smaller than 10^{-5}. All these values have reached their acceptable steady solutions during the simulation.

The solutions are also independent of the mesh resolution.

Boundary conditions

Boundary conditions for the above set up are as follows

i) Inlet to the domain : Velocity inlet, U_∞=1 m/s (U_∞=0 when inlet is a wall)
ii) Outlet from the domain : Gauge pressure outlet, p= 0 pascal
iii) Wall of the domain : No slip wall boundary (top and bottom s
iv) Cylinder wall surface : Temperature, T=1000 K(for both the cylinders)
v) Cylinder 1: Stationary/rotational wall
vi) Cylinder 2: Stationary/rotational wall

IV. RESULTS AND DISCUSSIONS

First of all, the mean drag coefficient, mean lift coefficient and Strouhal numbers of the isolated circular cylinder has been compared with that of the other researchers as mentioned in Table 1. The mean drag coefficient vs Re of the flow is plotted in Fig.2 . The comparison of the present values of the mean drag coefficient with the data published earlier is fairly good. The pathlines and contours of the mean velocity of flow around an isolated cylinder are shown in Fig. 3 whereas Fig.4 shows the Strouhal number of vortex shedding from the isolated cylinder. These results are taken for Re=200. The comparison and the validation of the approach have encouraged the authors to go for studying the flow variables when there is a flow over two heated circular cylinders. The mean drag coefficient, C_D^M, mean lift coefficient C_L^M and Strouhal number, St are compared with some of the leading references.

Table 1.Comparison of the mean drag coefficient C_D^M, $C_L^M$and St

	C_D^M	C_L^A	St
Present	1.41	0.692	0.1902
M-M Lui et al (2014)	1.337	0.685	0.1955
B.N. Rajani et al (2009)	1.3380	0.4276	0.1936
Wang et al(2009)	-	0.71	0.1950
Zhang et al (2008)	1.34	0.66	0.1970
Linnick and Fascl(2005)	1.34-1.37	0.71	-
Farrani et al (2001)	1.36-1.39	0.71	-
He et al (2000)	1.36	-	0.1978
Data compiled by Zdravkovich (1997)	1.43	-	-
Henderson (1995)	1.34-1.37	-	0.1971

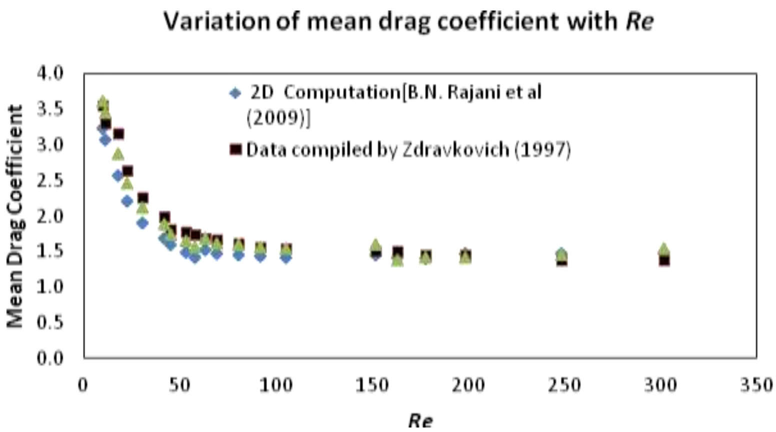

Fig.2: Comparison of Mean Drag Coefficients for various Reynolds number for a single circular cylinder

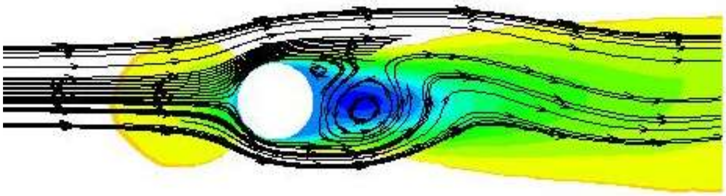

Fig.3 Instantaneous pathlines and mean velocity of flow over an isolated circular cylinder

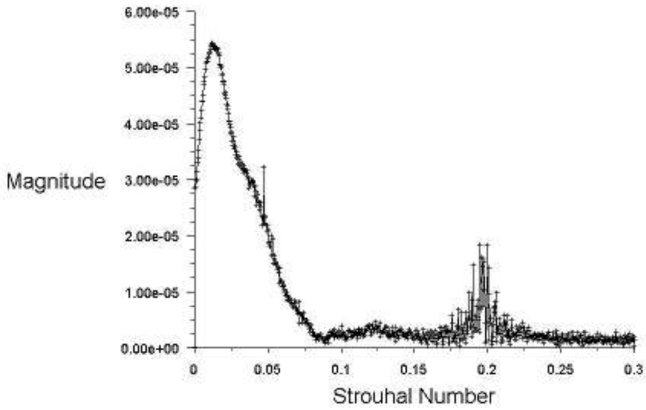

Fig.4 Strouhal number of vortex shedding from the isolated cylinder

Fig.5 shows the variation of total temperature around two heated and rotating cylinders (centers at x=0 m and x=3.7 m) in tandem arrangement. The total temperature has two components: static and dynamic. The dynamic part of temperature is a completely flow and nucleation driven one. So, convective heat transfer current set locally near the solid surface takes out heat from the solid surface and feeds into the bulk fluid, and colder and heavier fluid fills in the gap and gets heated locally. This movement of the lighter fluid leaving the heated surface, and the heavier ones landing on the solid surface, affects the overall temperature distribution around both cylinders. This variation is bound to happen in a new thermodynamic phase change process.

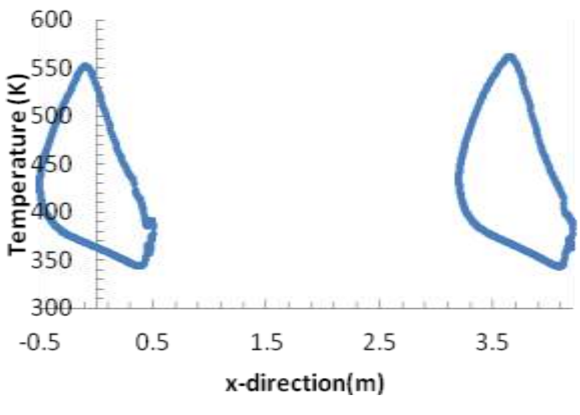

Fig.5 Total temperature around two heated and rotating cylinders (centers at x=0 m and x=3.7 m) in tandem arrangement

In Fig. 6, the Prandtl number (ratio of viscous diffusivity and thermal diffusivity) for the first cylinder is around 25% higher than that of the second cylinder. It is expected that the heat flux release at the first is more (viscous force is also more), and the heat flux release from the surface of the second cylinder is less because fluid flowing from the first cylinder takes away a certain amount of energy from the already releasing heat energy in the flow. Since Pr <1 in both cylinders it is believed that thermal diffusivity is more [mostly near the top of each cylinder] predominant. The viscous diffusivity seems to be lower because the kinematic viscosity decreases at a higher local surface temperature.

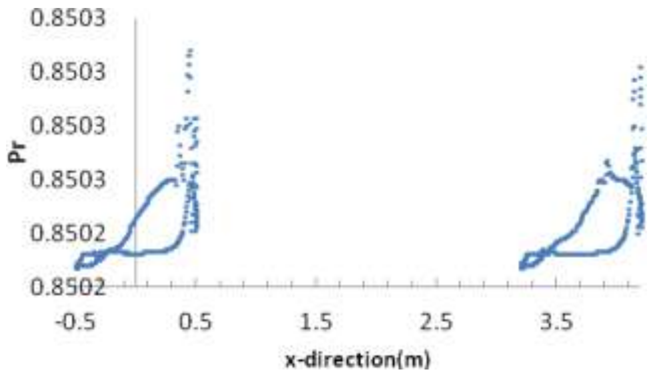

Fig.6 Prandtl Number distribution around two heated and rotating cylinders (centers at x=0 m and x=3.7 m) in tandem arrangement

Fig.7 shows Nusselt Number (Nu) distribution around two heated and rotating cylinders (centers at x=0 m and x=3.7 m) in tandem arrangement. This number is an indicator of heat transfer between a moving fluid and a solid surface. In both cylinders the Nu varies between 14 and 25. The higher values indicate that there is more convection than conduction at a specific location. The bottom surfaces have a higher Nu.

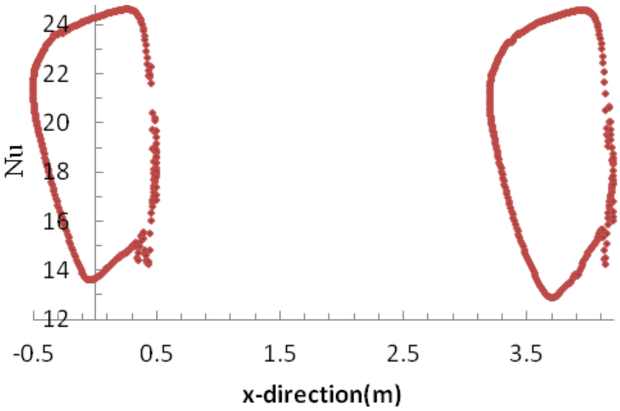

Fig.7 Nusselt Number distribution around two heated and rotating cylinders (centers at x=0 m and x=3.7 m) in tandem arrangement

Film Boiling Phenomenon during phase change process

Film Boiling phenomenon was studied when the L/D ratio is 3.7. Three sitations have been considered in this study.

(a) Water is initially stagnant and cylinders rotate

Walls are adiabatic.Cylinders rotate at 1000 rpm (104.71 rad/sec). Phase interaction is attributed to film boiling due to heat release from the surface of two cylinders of equal diameter and maintained at a temperature of 1000K. The surface temperature must be higher than the bulk temperature(373.5K). All the three walls (inlet, top and bottom) are treated as adiabatic and, the outlet is open with a backflow total temperature of 372 K. The contour plots shown in Fig. 8 is for the volume fraction of steam coming out of the surfaces of the rotating cylinders at 1000 K. The rpm is 1000 (104.71 rad/sec). The diameter of each cylinder is 1 m. The mass, momentum and heat transher from liquid phase to vapor phase is purely based upon film boiling situation.

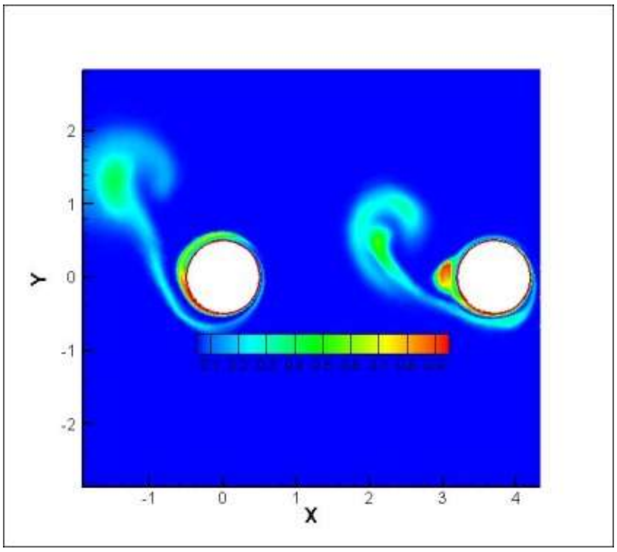

Fig.8 Contour plots shown is for the volume fraction of steam coming out of the surfaces of rotating cylinders (L/D=3.7) that kept at 1000K inside stagnant water

(b) Water flows from left to right over rotating cylinders

Water is in motion from the inlet to the outlet.Contour plots are shown in Fig. 9. The two cylinders rotate at 1000 revolutions per minute(rpm). Phase interaction is attributed to film boiling due to heat release from the surface of the two cylinders of equal diameter and kept at a temperature of 1000K. The two walls (top and bottom) are treated as adiabatic, The inlet has a velocity of 1 m/s, and the outlet is open with a backflow total temperature of 372 K.

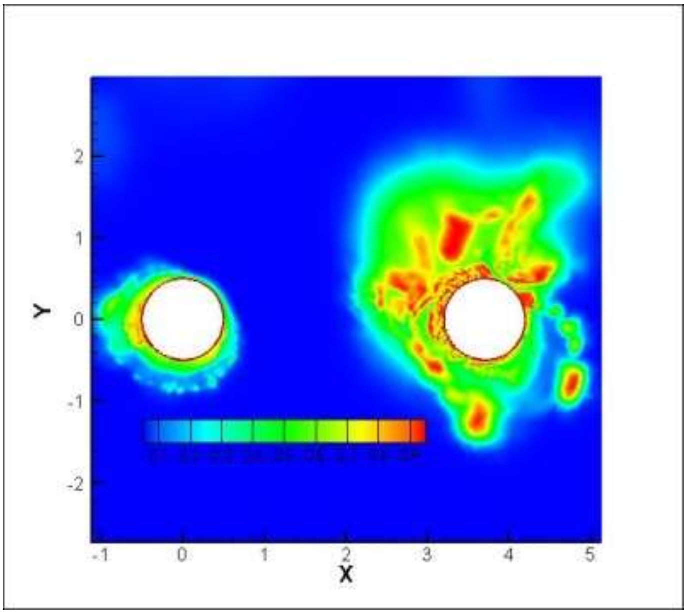

Fig.9 Contour plot is for the volume fraction of steam coming out of the surfaces of rotating cylinders (L/D=3.7) that kept at 1000K inside flowing water

(c) Water is stagnant and cylinders are stationary

Water is stagnat .Contour plot is shown in Fig. 10. The two cylinders are fixed Phase interaction is attributed to film boiling due to heat release from the surface of the two cylinders of equal diameter and kept at a temperature of 1000K. Near The cylinder 1 is visible the vapour and gradually the cylinder 2 experiences the presence of vapour.

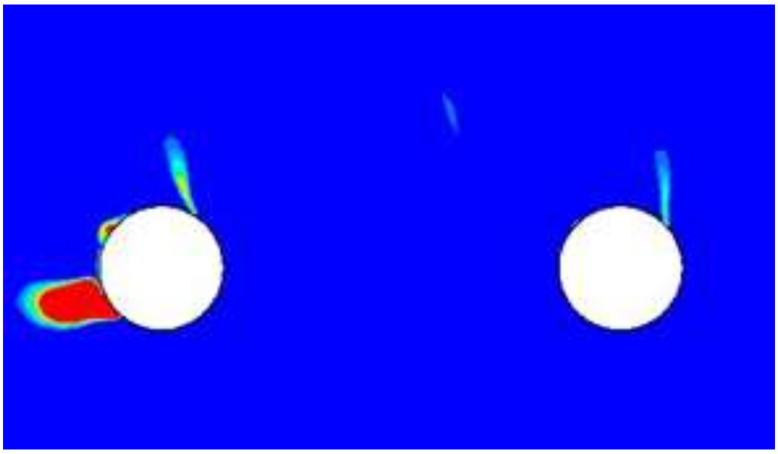

Fig.10 Contour plot is for the volume fraction of steam coming out of the surfaces of fixed cylinders (L/D=3.7) that kept at 1000K in stagnant water

The rotation of the cylinder influences the formation of steam by adding more heat due to local mixing and transfer of frictional energy to water. The film boiling phenomenon is the cause of mass, momentum and heat transfer from the solid surface [T_{solid}=1000 K] to bulk fluid. For the interaction between the two phases [water and steam] the condensation-evaporation option of the solver was adopted. The nucleation of a new phase, steam, initiates from the solid surface, grows with mass, momentum and energy and decays into the bulk of liquid (water). This self-assembly process of steam is quite noteworthy over time.

A comparison of VOFs of steam around each cylinder is given in Fig 11. For 3000 rpm the VOF values are around 30% higher than those obtained at 1000 rpm. The rotation of the cylinder aids in enhancing the VOF because it enables better convection heat transfer which in turn adds more heat into the bulk fluid. For zero rpm(stationary cylinders), the VOF is the lowest as depicted in the graph. In the Fig.12 similar observation is made for VOF. However, the variation of VOF between 1000 rpm and 3000 rpm cases is around 5-7%.

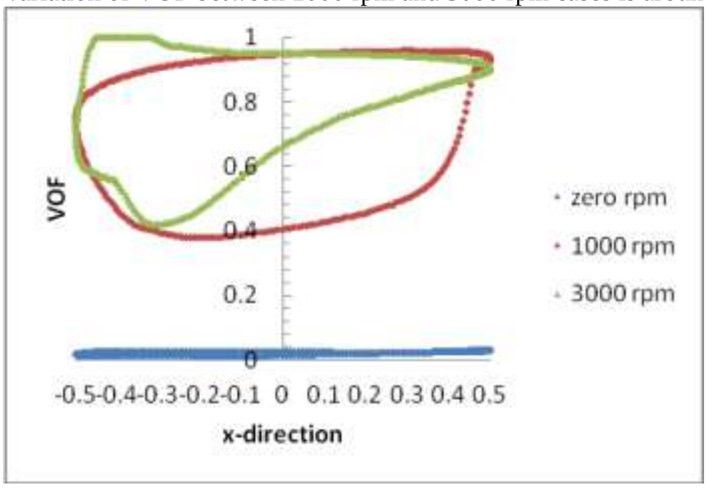

Fig.11 Variation of volume of fraction(VOF) of steam over cylinder- 1

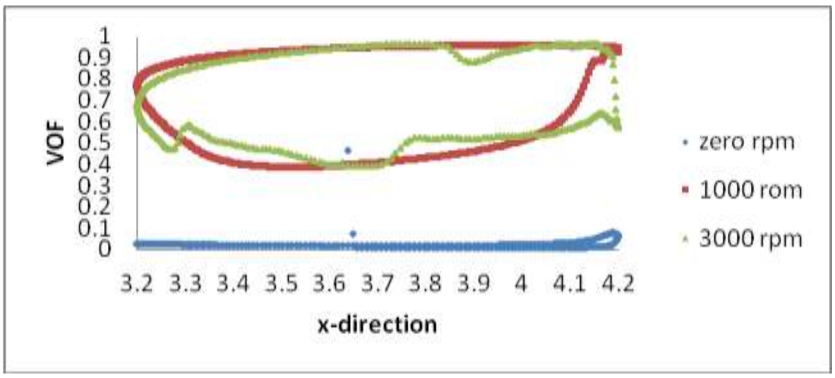

Fig.12 Variation of volume of fraction(VOF) of steam over cylinder- 2

V. CONCLUSION

The pathlines for an isolated cylinder and a two-cylinder arrangement are quite different, and hence significant differences exist between the study of flows over these two situations. The heated cylinders and the flow over them have given opportunity to investigate the heat flux release from the surface and its impact on the flow dynamics in the wake of the first and second cylinders. The Prandtl and Nusselt number variations, turbulent K.E. and other important variables were studied, and inferences were made on the correlation between the heat flux and the flow dynamics. The film boiling phenomenon during phase change from liquid to vapour phase has enhanced the understanding of the phase change process. The convective heat transfer and rotation of cylinders are strongly correlated, and hence VOF for 1000 rpm and 3000 rpm differs by 30%.

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