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A Study of Nucleate Boiling Phenomenon of Water Undergoing Phase Change over Two Rotating Heated Cylinders in Tandem Arrangement at Different Spacing and Surface Roughness

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Abstract- **In recent years, the problems of fluid flow interface and enhanced boiling heat transfer over an array of cylinders has emerged as a potential research area in technological developments of fluid dynamics and prominent industry applications such as cooling of electronic components, nuclear reactor fuel rods, etc. The mentioned applications are subjected to flow of water or air and experiences flow induced forces that will lead to the failure of structures over a long period of time. An attempt is made to study the effect of different spacing and surface roughness of two tandem cylinders over the nucleate boiling phenomenon of water undergoing phase change. The evaporation condensation model with RANS equation was used to establish the interaction between the two phases. There is a significant influence of spacing and surface roughness on the film boiling phenomenon that begins from the surface of a heated cylinder with better convective heat transfer. The formation of a new thermodynamic phase, its growth and decay were studied, and it is observed that the difference of about 57% in the VF values for 3 times rise in gap and the VF is down by 71% for increasing the surface roughness by 100µ.**

Keywords —Heat Transfer, Nucleate Boiling, Phase Change, RANS, Roughness, Tandem Cylinder.

I. INTRODUCTION

Forced convection heat transfer investigation over tandem cylinders is quite potential topic on which many research studies have been done in the past due to their wide practical applications [1]. Despite of simplicity in the design of geometry, they involve complex physics in fluid theory, including vortex shedding, fluid flow interaction and interference, fluid-structure interaction, flow induced vibration, transition from steady to unsteady flow conditions, etc. [2-12]. Cylindrical structures appear in a group over a variety of engineering applications such as cooling towers, energy harvesters, heat-exchanger tubes, compact heat exchangers, nuclear reactor fuel rods, chimney stacks and offshore structures. The mentioned structures experience flow induced forces that lead to structural failure over a long period of time [8-13]. With respect to free stream direction, the two cylinder model is used as the tractable baseline model to study the flow physics and they can be arranged in tandem, side-by-side and staggered configurations [6-16]. Given the above significance, several research activities have devoted in elucidating the cylinder spacing effect over the flow and heat transfer characteristics. In Summary it is therefore observed that the nature of comprehensive flow maps depends upon the arrangement of the cylinders [6-16].

Convection heat transfer over a cylinder submerged in water can be improved either by increasing the linear flow velocity or by the angular velocity of rotating cylinder with specific Reynolds number [11, 12 and 17]. The convective heat transfer due to the rotation of the cylinder depends upon the rotation speed/angular velocity in which the cylinder is rotating. The heat transfer coefficient will tend to decrease with increase in angular velocity and finally tends to zero as the frequency of bubble formation decreases [11, 12]. The boiling phenomenon occurs due to the formation of bubbles from the nucleate site when the cylinder surface temperature is higher than that of the saturation temperature of water, will gets ceased and the bubble formation halts. Thus, the heat transfer occurs only due to the forced convection.

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Several researchers have correlated boiling heat transfer mechanism from a rotating cylindrical surface. Their correlations differ above and below the critical speed [17]. It is observed that the Nusselt number is almost independent of the Reynolds number for rotational speeds from zero to a critical value [18].

$$Nu = 0.14(Gr\,Pr)^{1/3} \quad (1)$$

The critical Reynolds number was found to be equal to

$$Re_{cr} = 1.09(Gr)^{1/2} \quad (2)$$

Above critical Reynolds number, Grashof number will have a negligible effect on the rate of heat transfer. The buoyancy acceleration term ($\beta g \Delta T$) in the free convection equation for a horizontal surface was be replaced with a corresponding centrifugal term ($2U^2/D$) thus yielding,

$$Nu = 0.10(Re)^{2/3} \quad (3)$$

Becker [19] rearranged the correlation by introducing the Prandtl number in order to be applied in the general case of any liquid.

$$Nu = 0.111(Re)^{2/3}(Pr)^{1/3} \quad (4)$$

The effects of rotation were correlated by the inclusion of a Weber-Reynolds number term in the boiling equation of Lienhard [20]. The correlation for heat transfer over rotating surface below critical speed,

$$\frac{Q}{A} = 235(\Delta T)^{1.76}(k.l)(Pr)^{1/3}\left[1 + 178\left({}^{We}/_{Re}\right)^{0.63}\right] \quad (5)$$

Above the critical speed the same basic equation was modified to include a Froude number which gave rise to the below correlation [21],

$$\frac{Q}{A} = 520(\Delta T)^{1.76}(k.l)(Pr)^{1/3}(Fr)^{-0.186} \quad (6)$$

The above equations are numerically simulated to understand the behaviour of heat transfer from the cylinder over a range of Reynolds number and observations are reported [11, 17].

The understanding of nucleate boiling phenomenon during the phase of water flowing over two heated rotating circular cylinders in tandem arrangement is quite complex, and it has a direct impact over the vapor formation as the transfer of mass, momentum and heat happens from the cylinder to water. The cylinder spacing and the surface roughness has also direct influence on the phase change occurrence. The objective is to address the gaps mentioned and bring clarity to the complexities of phase change of water flowing over two heated rotating circular cylinders in tandem arrangement.

The specific problem is to assess how the nucleate boiling phase change process gets affected when the two phases interact and also to what could be the possible causes of variation in 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, comparison of VOFs of steam was made between the case when the two rotating cylinders have different diameters, the case with rotating cylinders of equal diameters varied with cylinder spacing between them and the case when the same cylinders have different surface roughness immersed in the flowing water. The evaporation-condensation model was used to establish the interaction between the two phases.

II. GOVERNING EQUATIONS

The mass, momentum and energy conservation equation of the time-averaged equation is considered for the present study:

Mass Conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (7)$$

Momentum Conservation equation:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial(\rho u_i u_j + P\delta_{ij})}{\partial x_j} = \frac{\partial(\tau_{ij} - \rho\overline{u_1 u_j})}{\partial x_j} \quad (8)$$

Energy Conservation equation:

$$\frac{\partial(\rho e_o)}{\partial t} + \frac{\partial(\rho e_o u_i + P u_i)}{\partial x_i} = \frac{\partial(\tau_{ij} - \rho\overline{u_1 u_j} u_j)}{\partial x_i} - \frac{\partial(q_i - C_p \rho \overline{u_1 \theta})}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\left(\mu_1 + \frac{\mu_i}{\overline{\sigma k}}\right)\frac{\partial k}{\partial x_i}\right] \quad (9)$$

Turbulence Models:

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

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho u_i k}{\partial x_j} = -\rho\,\overline{u_j u_1}\frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\mu_1 + \frac{c_\mu k^2}{\overline{\sigma k^\varepsilon}}\right)\frac{\partial k}{\partial x_j}\right] - \rho\varepsilon(1 + M_\tau^2) \quad (10)$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial \rho u_i \varepsilon}{\partial x_j} = -C_{\varepsilon 1}\rho\,\overline{u_j u_1}\frac{\partial u_i}{\partial x_j}\frac{\varepsilon}{k} + \frac{\partial}{\partial x_j}\left[\left(\mu_1 + \frac{c_\mu k^2}{\overline{\sigma k^\varepsilon}}\right)\frac{\partial \varepsilon}{\partial x_j}\right] - f_2 \rho \overline{C_{\varepsilon 2}}\frac{\varepsilon}{k}\left[\varepsilon - V_1\left(\frac{\partial\sqrt{k}}{\partial n}\right)^2\right] \quad (11)$$

where,

$$C_\mu = 0.09, C_{\varepsilon 1} = 1.44, \overline{\sigma k} = \sigma k = 1.4, \overline{\sigma \varepsilon} = \sigma\varepsilon = 1 \text{ and } \overline{C_{\varepsilon 2}} = C_{\varepsilon 2} = 1.92$$

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

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

$$\varepsilon_{wall} = V_1\left(\frac{\partial\sqrt{k}}{\partial n}\right)^2; \; k_{wall} = 0$$

The turbulent stress components are

$$\rho\overline{u_j u_1} = 2\rho V_t S_{ji} - \frac{2}{3}\delta_{ji}\rho k \text{ and}$$

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

III. METHODOLOGY

The major objective of this research work would be to suggest an appropriate approach for using the heat from the cylinders and observing the change in VOF using numerical simulations. This specific problem is to demonstrate how nucleate boiling affects the phase change phenomenon when cylinders rotate at a particular speed spaced at different distances, and what could be the possible causes of fluctuation in volume fraction of water (liquid phase) and steam (vapor phase) when the cylinder surface roughness is varied while the flow is stagnant or in motion.

For the flow over cylinders, the continuity, momentum and energy equations are solved. Fig.1 illustrates the general numerical set-up for two circular cylinders in tandem arrangement with the boundary conditions adopted. All dimensions in fluid domain are expressed in terms of cylinder diameter. Components of velocity in X-Y direction are u and v respectively, T is the inlet flow temperature, flow with free stream velocity is from left to right in the domain. Both the cylinders are maintained at wall temperature (T_{wall}) specified at the boundary. The research problem described is solved by deploying a commercially available CFD (computational fluid dynamics) solver Ansys® Fluent 12.0.

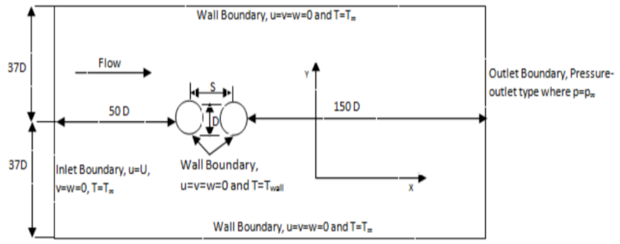

Fig.1: Numerical set-up (x-y plane) for two circular cylinders in tandem arrangement with boundary conditions

Convergence and Mesh Independence Study

The convergence of numerical solutions is obtained by the residual values of variables. SIMPLE algorithm is used for the solution method. In the present work, three alternative grid sizes were considered to see whether the solution was independent of grid alterations (illustrated in Fig.2 and Fig.3). The convergence criterion for all variables involved in the computation is absolute and fixed at 10^{-5}. Convergence occurs when the values of total residual become smaller than 10^{-5}. As shown in the Fig.4, convergence of all solution variables is obtained in one of the cases considered in the study, the variation in values of the flow variables obtained from the three different grid arrangements is much lesser than 1%, and the residual value set during convergence of solution is 10^{-5} for flow variables. All the values have reached the acceptable steady solutions and the solutions are independent of mesh resolution.

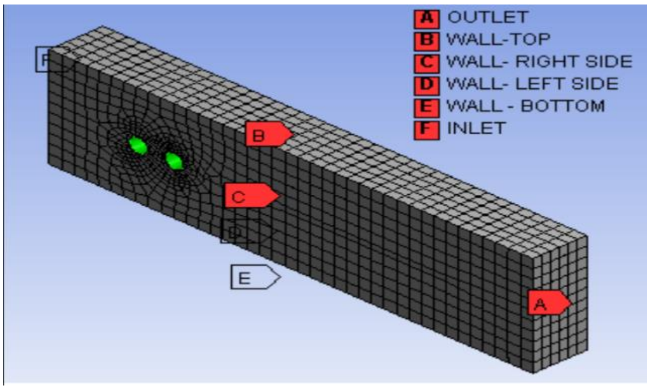

Fig.2 Fluid flow domain, cylinders arranged in tandem and their mesh

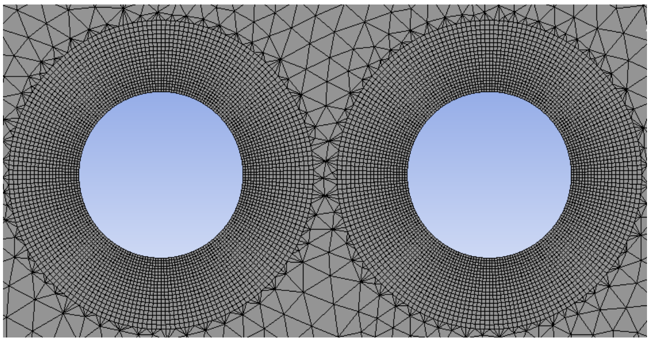

Fig.3 Unstructured tri/quad mesh (quality =0.9) used for the domain

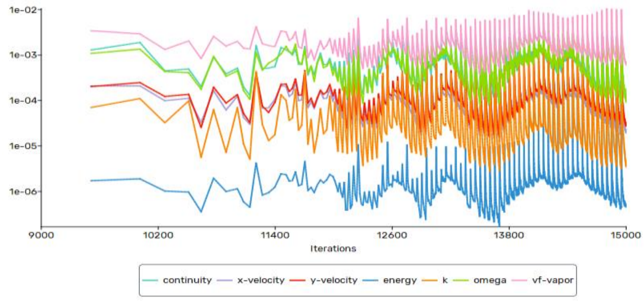

Fig.4 Convergence of solution variables

Boundary conditions

Boundary conditions for the above mentioned set up used in numerical analysis are as follows:

i) Inlet to the domain : Free stream 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) Walls of the domain : No-slip wall boundary (top and bottom surfaces) (u=v=0)

iv) Cylinder wall surface : Temperature, T = 393 K (for both the cylinders)

v) Cylinder 1 : Stationary/rotational wall

vi) Cylinder 2 : Stationary/rotational wall

vii) Temperature of water in the domain is maintained at 373.5 K

IV. RESULTS AND DISCUSSION

Research work is carried out and analyzed in three different cases using Ansys® Fluent as solver.

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CASE 1: Two cylinders are placed in tandem arrangement, the first cylinder facing the flow is at diameter 'D=2d' and the second cylinder is at diameter'd', while both cylinders are rotating at an angular speed, (ω = 104.7 rad/s or 1000 rpm) and linear velocity of water (U_∞=1 m/s). Three different cylinder spacing /gaps are considered (2d, 4d and 6d).

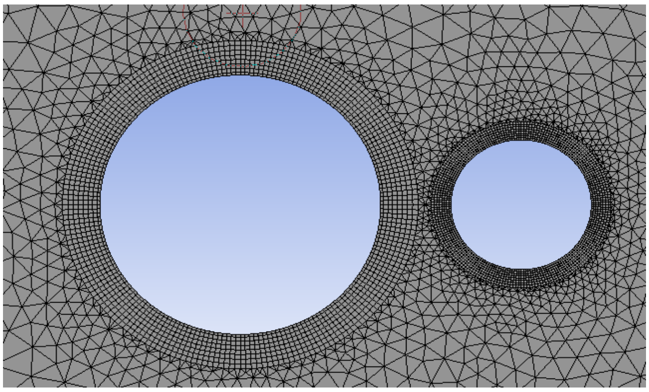

Fig.5 Tri/Quad Meshing in the flow domain

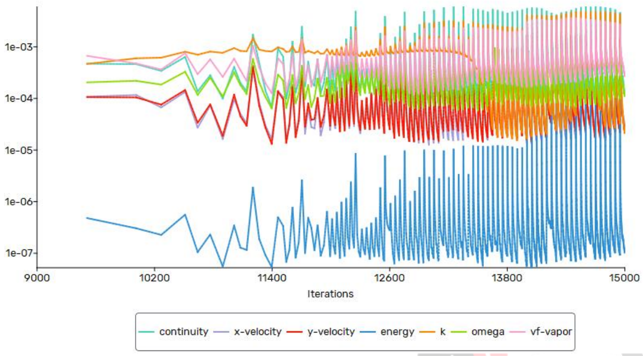

Fig.6 Convergence of solution variables

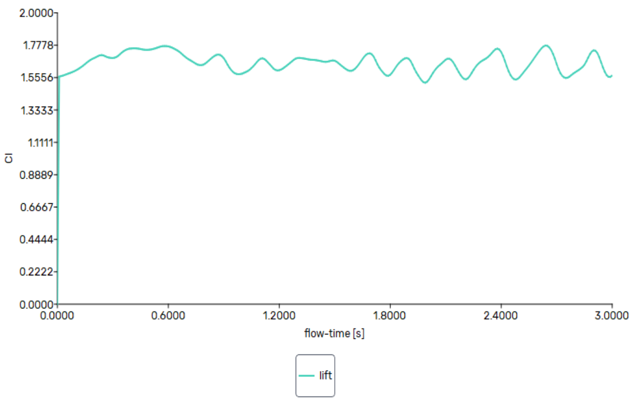

Fig.7 Lift Coefficient versus Flow Time in Seconds

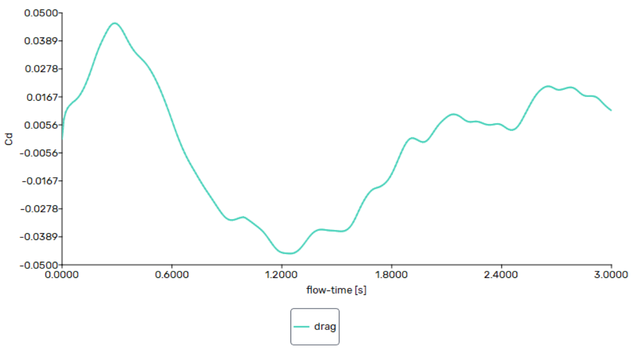

Fig.8 Drag Coefficient versus Flow Time in Seconds

The time dependent two dimensional lift coefficient (C_l) and drag coefficient (C_d) are obtained by integrating the surface pressures [22],

$$C_l(t) = \frac{1}{2}\int_0^{2\pi} C_p(t)\sin(\theta)\,d\theta\,, \qquad (12)$$

$$C_d(t) = \frac{1}{2}\int_0^{2\pi} C_p(t)\cos(\theta)\,d\theta\,, \qquad (13)$$

Where, 'θ' is the angular position from the leading stagnation point of the cylinder. These lift and drag coefficients are necessary to be observed because the heat and mass transfer between the solid surface of cylinder and the fluid layers are affected by both the drag and lift. It is noted that the drag is though negligible the lift coefficient is maintained between 1.5 and 1.7. It indicates that the possibility of presence of buoyancy force (may be caused due to the centrifugal force of rotating cylinder) is one aspect of faster heat and mass exchange when rotational speed increases.

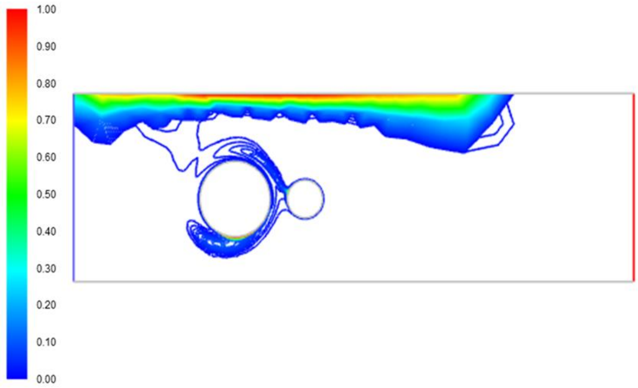

Fig. 9 VF at 1000 rpm with spacing of 2d

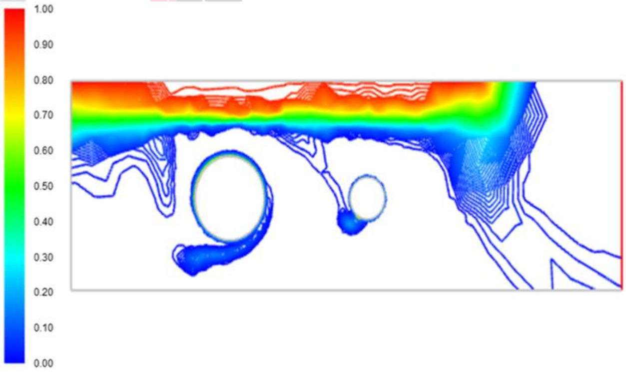

Fig.10 VF at 1000 rpm with spacing of 4d

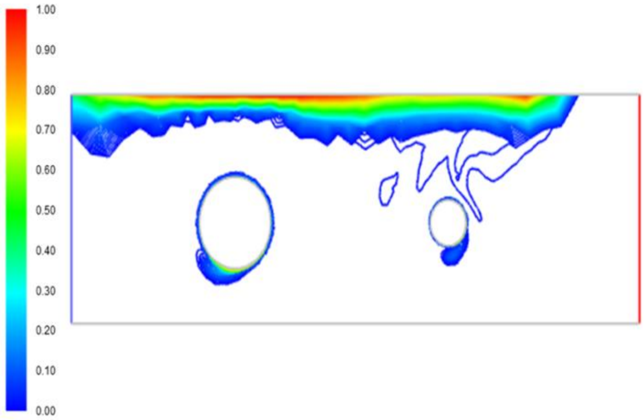

Fig.11 VF at 1000 rpm with spacing of 6d

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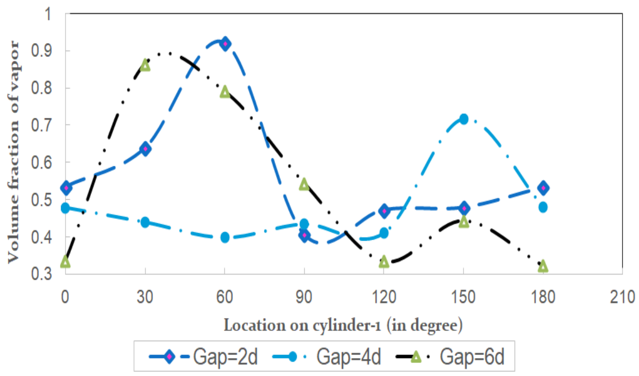

Fig.12 Volume fraction (VF) of vapor at different locations of cylinder -1 (Dia=2 times'd') when the gaps of 2d, 4d and 6d are maintained between cylinder-1 and cylinder-2

Vapor fraction of water vapor for both the cylinders and when the flow is from left to right is observed and reported in the above Fig.8-10. Volume fractions (VF) of vapor at different locations on cylinder -1 when the gaps of 2d, 4d and 6d are maintained are reported in Fig.11. Overall rise in VF by 23% is obtained for 2 time's rise of diameter (2d). Overall down in VF by 51% is observed for 3 time's rise of gap/spacing between the cylinders (6d).

CASE 2: Two cylinders are placed in tandem arrangement, both the cylinders are at equal diameter 'd', while both cylinders are rotating at an angular speed, (ω = 104.7 rad/s or 1000 rpm) and linear velocity of water (U_∞=1 m/s). Three different cylinder spacing/gaps are considered (2d, 4d and 6d).

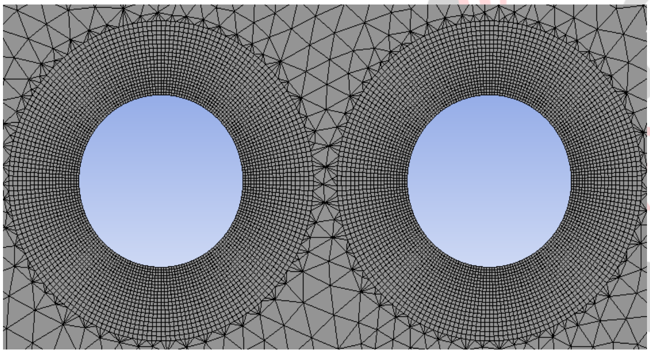

Fig.13 Tri/Quad meshing in the flow domain, 40 layers of inflation near the solid walls.

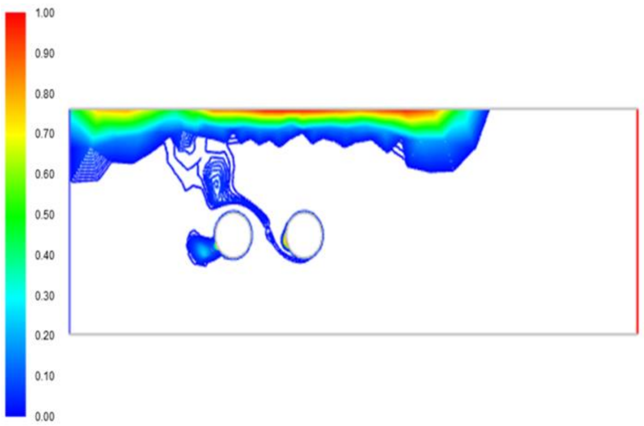

Fig.14 VF at 1000 rpm with spacing of 2d

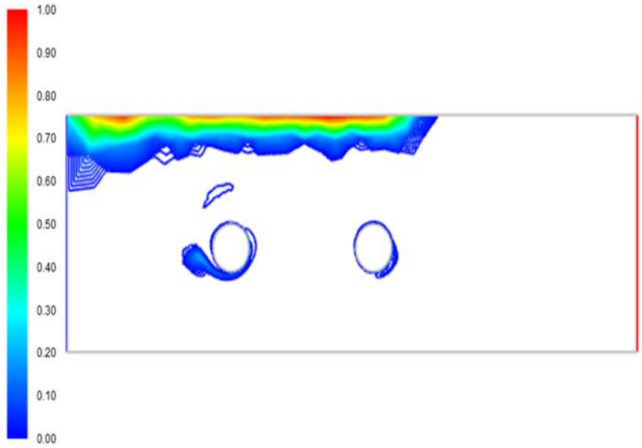

Fig.15 VF at 1000 rpm with spacing of 4d

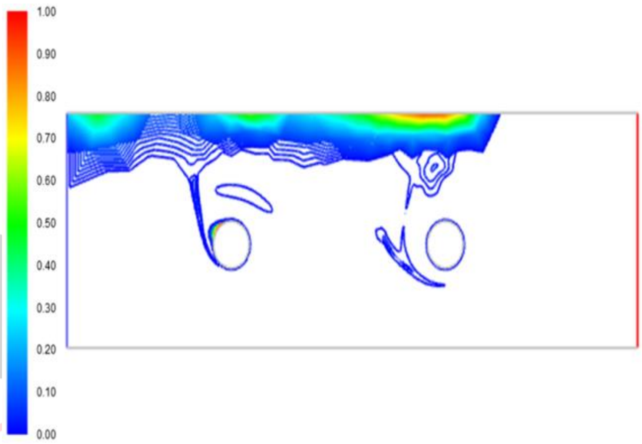

Fig.16 VF at 1000 rpm with spacing of 6d

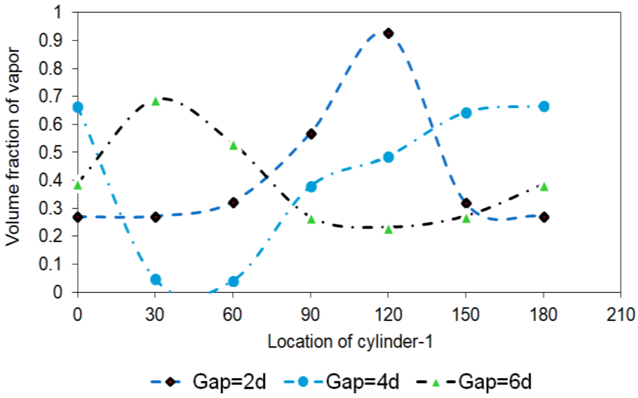

Fig.17 Volume fraction (VF) of vapor at different locations of cylinder -1 (dia=2 times of 'd') when the gaps of 2d,4d and 6d are maintained between cylinder-1 and cylinder-2

Vapor fraction of water vapor for both the cylinders and when the flow is from left to right is observed and reported in the above Fig.13-15. Volume fractions (VF) of vapor at different locations on cylinder -1 when the gaps of 2d, 4d and 6d are maintained are reported in Fig.16. Overall rise in VF by 57% is observed for 3 time's rise of gap/spacing between the cylinders (6d).

CASE 3: Three different surface roughness values are considered (smooth surface, 50 microns and 100 microns).

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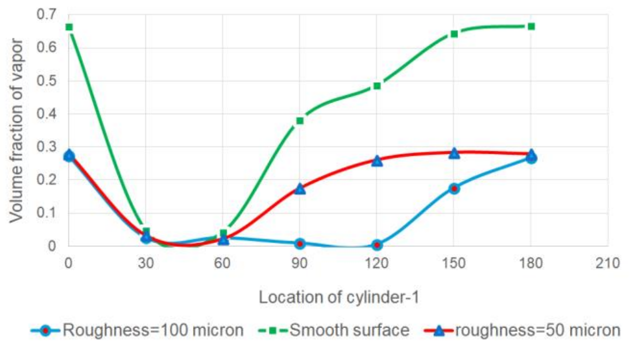

Fig. 17 Comparison of volume fraction (VF) of vapour over cylinder-1 when its rpm is 1000 at different surface roughness

Volume fractions (VF) of vapor at different locations on cylinder -1 rotating at 1000 rpm with the surface roughness values are varied from smooth to 50 microns and 100 microns are reported in Fig.17. Overall VF is down by 71% for 2 times rise in surface roughness (100 microns). The Results obtained in the three different cases discussed above are tabulated in the Table 1.

Table 1: Result summary of all the three cases studied over different locations on cylinder-1

Case : Water flows while the cylinders rotate at 1000 rpm. The effect of -	**VF at Different Locations on Cylinder -1**			**Remark**
	VF at 0°	**VF at 90°**	**VF at 180°**	
Unequal Cylinder Diameter: Increasing size of cylinder-1 (D → 2d) **Spacing Gap**: 2d/4d/6d between the two rotating cylinders	(Rise by 49%) 0.27/0.53 (Down by 37%) 0.53/0.48/0.33	(Down by 28%) 0.56/0.40 (Rise by 25%) 0.40/0.43/0.54	(Rise by 49%) 0.27/0.53 (Down by 39%) 0.53/0.48/0.32	Overall rise is 23% for 2 times rise of diameter Overall down by 51% for 3 times rise of gap
Equal Cylinder Diameter: Size of cylinders (D → d) **Spacing Gap**: 2d/4d/6d between the two rotating cylinders	(60% rise) 0.26/0.39/0.66	(51% rise) 0.27/0.38/.56	(59% rise) 0.27/0.38/0.66	Overall rise in VF is 57% for 3 times rise in gap
Surface Roughness: Smooth Surface/ Roughness of 50μ / Roughness of 100μ	(Down by 59%) 0.66/0.27/0.27	(Down by 97%) 0.38/0.17/0.009	(Down by 59%) 0.67/0.28/0.28	VF is down by 71% for 2 times rise in surface roughness

V. CONCLUSIONS

In summary, comprehensive VF flow maps over two rotating heated cylinders in tandem arrangement are presented in this study, including the flow domain, flow boundaries, volume fractions of water vapour over the cylinders at various locations. The heated rotating cylinders and the water flow over them have given an opportunity to investigate the heat flux release from the surface during nucleate boiling and its impact on the flow dynamics in the wake of the first and second cylinders. The nucleate boiling phenomenon during phase change from liquid to vapour has enhanced the understanding of the phase changing process. The rotation of cylinders, spacing between the cylinders, surface roughness and convective heat transfer are strongly correlated, and hence VF for 1000 rpm with 1 m/sec water flow over three different cases were observed and reported here. The impact of increasing size of cylinder-1 (d → 2d) with a variation in spacing gap between two cylinders from 2d to 6d has been studied. Overall rise in VF is 23% for 2 times rise of diameter, while Overall down in VF by 51% for 3 times rise of gap. The impact of spacing between two tandem cylinders having equal diameter on VF has been studied. The difference of about 57% is observed in the VF values for 3 times rise in gap. The impact of cylinder surface roughness (in microns) on heat transfer rate is investigated. VF is down by 71% for increasing the surface roughness by 100μ.

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