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Influence of Blade Shape and Water Droplet Size on Fractional Deposition in the Last Stages of Steam Turbine

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***Abstract* — The improvement in Rankine steam cycle power generation efficiency is dependent upon lowering heat rejection during condensation for enhanced work ratio that is limited by allowable wetness of steam at turbine exhaust. In this paper the influence of the blade shape and droplet size on the deposition in the last stage blades of the condensing steam turbine is investigated. The blade profile of the steam turbine has been adopted from an experimental set up along a reference test case. While passing through the lowest pressure stages of turbine, steam crosses the saturation line with a variable wetness thus reducing the efficiency of the turbo-cylinder. These water droplets deposit on the stator guide blade surface, and coagulate in to films and rivulets, which are dragged towards the trailing edge by viscous drag. The large droplets then hit the rotor blade due to strong aerodynamic force which causes erosion on the rotor blade surface. The two prominent phenomenons responsible for deposition in blade surface are inertial impaction and turbulent-diffusion. With increasing stagger angle, the fractional deposition departs highly from single value from leading edge to trailing edge showing strong influence of blade shape on fractional deposition. From this background, the aim of this work is to analytically outline the unsaturated water vapour condensing mechanism in lowest pressure stages of steam turbine and investigate the influence of droplet size and rotor blade profile on deposition.**

***Keywords* — steam turbine, droplet, deposition, blade shape, droplet size, inertial deposition, diffusional deposition.**

NOTATION

A Area
$C\infty$ Volumetric Concentration of Droplets outside Boundary Layer
D Diffusion Coefficient of Droplets
E Total Energy
h Enthalpy
I Nucleation Rate
Kn Knudsen Number
lg Mean Free Path of Vapor Molecule
N Mass Transfer Rate of Droplets to the Surface
n Size Distribution of Droplets
P Pressure
q Heat Flux
R Universal Gas Constant
Re Reynolds's Number
r Radius of Mono dispersed Droplets
Sc Schmidt Number
s Entropy
T Temperature
u Velocity along X direction
$u\tau$ Friction Velocity
$u+$ Dimensionless Friction Velocity
V Deposition Velocity of Droplets
V Vector form of Velocity
$V+$ Dimensionless Deposition Velocity of Droplets
v Velocity along Y direction
w Velocity along Z direction
y Distance from the Wall
$y+$ Dimensionless Wall Coordinate
i,, Unit Vectors
β Wetness Fraction
γ Specific Heat Ratio
Γ Mass Generation per Unit Volume
ϵ Eddy Diffusivity
η Number of Droplets per Unit Volume
μ Dynamic Viscosity
ν Kinematic Viscosity of the Fluid
ρ Fluid Density
σ Liquid Surface Tension
τ Stress Tensor
τr Inertial Relaxation Time
τw Wall Shear Stress
$\tau+$ Dimensionless Inertial Relaxation Time of the Droplets
Subscripts:
l Droplet
g Vapour
s Saturation Condition
x,, Coordinate axis

I. INTRODUCTION

Steam turbine blade erosion at the lowest pressure stages of expansion due to wet steam is a long standing problem. During 1960s to 1970s a significant amount of researches were carried out for developing the higher capacity of the steam turbines for power generating alternator capacity of 500 MW to 660 MW. This resulted into introduction of large last stage turbine blades of more than one meter length having high tip speed causing erosion due to condensate deposition from wet steam.

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This motivated the study of deposition models with experimental setups which studied the deposition of air particle for the validation. But the experimental results were quite large as compared with mathematical models. Subsequently, during 1980s, the developed optical instruments and probes were capable enough to measure droplet size distribution and flow rates. Following this period, the focus of research was mainly on aerodynamic blade design and efficiency. Off late, with the introduction of large steam turbines for 800 MW and above, need of retrofitting once again encouraged the study of droplet deposition. Unfortunately, then the computational science were not so reliable, and therefore, mostly correlation pattern of experimental results were used for assessment [1].

Taking the account of the past investigations on process of wet steam deposition in turbine blades, few noteworthy literatures are available and some useful works on experimental and numerical studies was carried out by Bhaktar et al. [2, 3] and White et al. [4]. Complex flow physics was encouraged for simplified 2D numerical studies, based on inviscid time marching scheme with Lagrangian tracking by White and Young [5], Bhaktar et al. [6]. Gerber and Kermani [7], Seeno and Shikano [8] worked on Eulerian-Eulerian multiphase method of condensing steam flow. The effect of droplet size and inter-phase friction on deposition was illustrated by Starzmann et al. [9]. The result of these works was quite satisfactory and agreed well with experiments.

But very little work till date is carried out on steam turbine droplet deposition. Large number of studies on phenomenon of diffusion deposition in turbulent flow pipes was investigated by Friedlander and Johnstone [10] on deposition rate of dust, based on transport of particles in turbulent stream; the work of Montgomery and Corn [11] studied complete turbulent flows with high Reynolds number for large pipes. Benjamin et al. [12] investigated on mono dispersed wide sized particles and dimensionless relaxation time. The noteworthy mathematical works by Cleaver and Yates [13] of sub-layer diffusion and the findings of Reeks and Skyrme [14] illustrates that with the increase in particle size, the deposition is controlled by diffusion as well as inertial mechanism whereas both are particle inertia dependent. Shobokshy and Ismail [15], Wood [16] explained the surface roughness dependency on droplet deposition. Parker and Lee [17], Parker and Reyley [18] worked on experimental investigation on the same issue, which is as well noteworthy.

The detailed work of Gyarmathy [19] and comprehensive study by Crane [1] on droplet deposition with relevance to steam turbine serves a good back ground for research. After crossing the saturation line steam does not condense immediately, it become supersaturated which is a meta-stable state. Reversion to equilibrium state happens with the large number of droplets of varying size that ranges from 0.05 - 1µm. These droplets deposits on the blade surface which coagulates in to films and rivulets which are dragged towards the trailing edge by viscous drag. These large droplets then hit the rotor blade due to strong aerodynamic force which causes erosion on the blade surface. The two prominent phenomenons responsible for deposition in blade surface are inertial impaction and turbulent-diffusion. The previous notable works have described the influence of droplet size whereas there is considerable influence of blade shape on deposition as well. Especially inertial deposition has strong relation with blade shape. The single deposition fraction can be defined when the blade has simple profile of low stagger angle. With the increase in stagger angle the fractional deposition departs highly from single value from leading edge to trailing edge. Therefore blade shape has strong influence on fractional deposition. From this background, the aim of this work is to describe the deposition mechanism in steam turbine in detail and investigate the influence of droplet size and blade profile on deposition.

II. Mathematical Models

Eulerian- Eulerian approach was adopted by means of ANSYS CFX 15 code for the investigation. Compressible flow equation with 2D approach is solved for modelling two phase fluid where steam is in continuous phase and liquid being the droplet with phase change.

A. Governing Equations

The governing equation of mass, momentum and energy for a mixture of liquid and vapour for an arbitrary volume dV and surface area dA can be written as:

$$\frac{\partial W}{\partial Q}\frac{\partial}{\partial t}\int Q dV + \oint M dA = \int N dV \quad (1)$$

Where :
$$W = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{pmatrix}, Q = \begin{pmatrix} P \\ u \\ v \\ T \end{pmatrix}, M = \begin{pmatrix} \rho v \\ \rho v u + P\hat{\imath} - \tau_{xi} \\ \rho v u + P\hat{\imath} - \tau_{yi} \\ \rho v E + P v - \tau_{ij} v_j - q \end{pmatrix}$$

The equation for mixture of vapour-liquid can be written as:

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$$\phi_m = \phi_l \beta + (1-\beta)\phi_v \quad (2)$$

The ϕ from the above equation denotes h, s, C_p, C_v, μ

The transport equations for condensed liquid phase mass fraction and number of droplets per unit volume are:

$$\frac{\partial \rho \beta}{\partial t} + \nabla.(\rho \vec{v} \beta) = \Gamma \quad (3)$$

$$\frac{\partial \rho \eta}{\partial t} + \nabla.(\rho \vec{v} \eta) = \rho I \quad (4)$$

In the above equations Γ, I represents the mass generation per unit volume and nucleation rate respectively. It is hypothesized that the interaction between water droplets and vapour surrounding them is negligible which is quite good consideration as the size of the droplets are very small in the order of 1 μm or less.

B. Deposition Phenomenon

The two deposition phenomenon namely turbulent diffusion mechanism and inertial deposition impaction are currently taken into consideration.

B-1 Turbulent diffusion mechanism: Turbulent diffusion mechanism is boundary layer phenomenon. When the steam passes over the blade surface the droplets gets deposited by turbulent diffusion through the boundary layer.

During mass transfer of droplets on the surface depositional velocity is a crucial parameter [20], where $V = {}^{N}/_{C_\infty}$, and the dimensionless depositional velocity can be written as $V_+ = {}^{V}/_{u_\tau}$, V_+ is the function of dimensionless inertial relaxation time defined as τ_+. Therefore, $V_+ = f(\tau_+)$. Physically, the relaxation time is defined as the time required by the droplets to accelerate to match the velocity of vapour. Inertial relaxation time (τ_r) can be formulated as [20]:

$$\tau_r = \frac{2\, r^2\, \rho_l}{9\, \mu_g} (\phi(Re) + 2.7\,\text{Kn}) \quad (5)$$

Where, $\text{Kn} = {}^{l_g}/_{2r}$ and

$\phi(Re) = [1 + 0.197\, Re^{0.63} + 0.00026\, Re^{1.38}]^{-1}$ and $\tau_+ = {}^{\tau_r u_\tau^2}/_{v_g}$ Equation (5) is a combined formula that can be used in both regimes namely continuum regime (Kn<<1) and free molecular regime (Kn>>1). Many works are available on deposition with context to pipe flow, whereas very little work can be found regarding droplet deposition on turbine blades.

However the study for pipe flows is well enough to study deposition on turbine blades. The depositional regimes namely Turbulent Particle-Diffusion Regime, Eddy-Diffusion Impaction Regime, and Particle Inertia-Moderated Regime can be identified as depicted in the figure 1. The key features of regimes are mentioned below.

Turbulent Particle-Diffusion Regime:

i) $\tau_+ < 0.1$

ii) Transport of particles by Brownian and eddy-diffusion where deposition rates are very slow and decreases with increase in particle size.

iii) $V_+ = f(\tau_+, Sc)$ where $Sc = v_g / D$

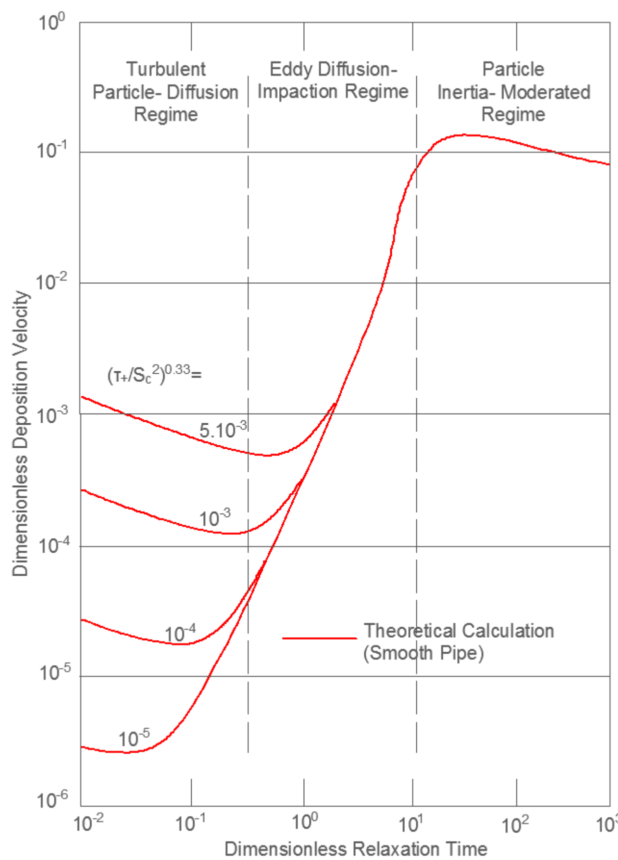

Figure 1: Diffusion Deposition Regimes in Turbulent Pipe Flow (modified) [20]

Eddy-Diffusion Impaction Regime:

i) $0.1 < \tau_+ < 10$

ii) Rapid increase of deposition for larger particles.

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iii) Transportation is due to intermittent turbulent bursts of fluid which disrupts the sub layer.

Particle Inertia-Moderated Regime:

i) $\tau_+ > 10$

ii) Deposition rate decreases.

iii) High inertia particles (large particle) damps the response of turbulent eddies.

The one equation that represents diffusion velocity in three regimes can be written as:

$$V_+ = \left(\frac{D}{v_g} + \frac{\epsilon}{v_g}\right)\frac{\partial c_+}{\partial y^+} \quad (6)$$

Where $c_+ = {}^{C}/_{C_\infty}$ and $D = \frac{K\,T_g}{6\,\pi r \mu_g}(1 + 2.7\mathrm{Kn})$

Integrating the equation (6) gives the values of droplet depositional velocities and hence droplet mass deposition.

B-2 Inertial Deposition: As the droplet size increases the droplets cannot follow the highly curved path followed by vapour due to high inertia. This causes the droplets to deposit on the blade surface.

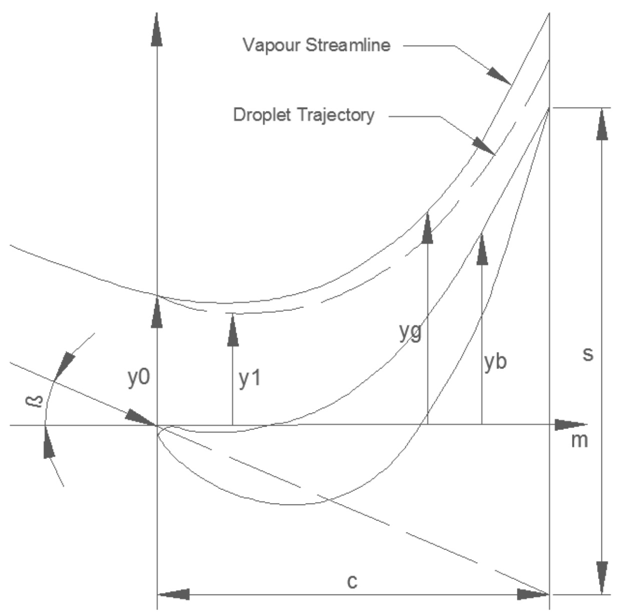

Figure 2: Geometric details of condensed water droplet deposition on pressure surface (modified) [21]

The equation of the stream line can be written as [26]:

$$y_g = y_0 - m\tan\beta + {sm^2}/_{c^2} \quad (7)$$

Where 'c' is meridional chord and β is the flow angle. The locus of droplet is given by:

$$y_l = y_b + y_0 - 2s(St)(1-\alpha)\left[\left(\frac{m}{c}\right) - St\left(1 - e^{-m/c\,St}\right)\right] \quad (8)$$

Where 'St' is the stokes number 'α' is the coriolis acceleration on the droplets.

III. Experimental Observation

The observation on experiment carried out by Crane [1] using a variable-incidence flat plate vertically in an unsaturated steam tunnel was as follows:

1. A thin surface film of water resulting from inertial deposition.
2. Apparent evaporation of the film, with occasional streaks.
3. Breaking away
4. An unsteady zone of finely dispersed water, oscillating rapidly in the stream wise direction with amplitude similar to its stream wise extent, about 5 mm.
5. A region of stationary globules, from the downstream end of which the globules either evaporated or were broken up and accelerated.
6. The pattern was similar with a sharp leading edge, except that feature (1) was absent."

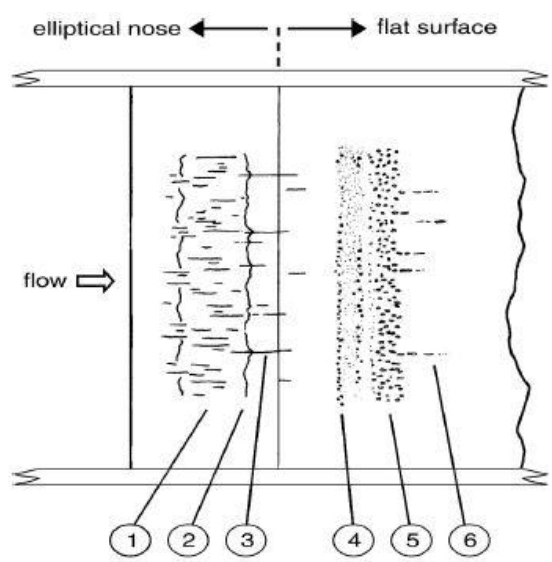

Figure 3: Fog droplets deposition pattern [1]

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IV. RESULTS & DISCUSSIONS

Based on the theories mentioned above, the numerical simulations have been performed by steady state 2D Reynolds Averaged Navier Stokes equations in Ansys CFX. The mixture of liquid-vapor is discretized using conservative finite-volume integration over a control volume with a multi-grid method. High resolution is set for advection scheme and turbulence numerics.

A. Test Case

The experimental results presented by White et al. [4] for a fifth stage stator blade profile of a six stage cascade of 660 MW LP steam turbine was adopted for present analysis. A specific case is chosen for the present study as shown in Table 1.

The simulations were performed with five different sets of mono-dispersed droplet size as mentioned in Table 2.

TABLE I
EXPERIMENTAL DATA

Upstream			Downstream
Stagnation Pressure P01 (mbar)	Stagnation Temperature T01 (K)	Stagnation Superheat T01-Ts (deg)	Mean Static Pressure P2 (mbar)
419	350	wet (1.6%)	178

TABLE III
DROPLET RADIUS

Nomenclature	R1	R2	R3	R4	R5
Radius (µm)	0.4	0.6	0.8	1.0	1.2

B. Grid Independency

The Grid Independency test is very important to test the solutions are independent of mesh. Three mesh are formed namely Mesh 1 (M1), Mesh 2 (M2), Mesh 3 (M3) and the details are mentioned in Table 3.

TABLE IIIII
DETAILS OF FINAL GRID

Mesh	Nodes	Elements	Aspect Ratio (Min.-Max.)	Skewness (Min.-Max.)	Orthogonal Quality (Min.-Max.)
1	39620	38875	1.81-8.33	2.69e-2-0.502	0.837-0.982
2	79140	78200	3.11-7.34	2.69e-2-0.503	0.7-0.983
3	93560	92600	4.54-10	2.68e-2-0.503	0.787-0.976

The figure 4 depicts that M1 does not produce good results whereas M2 and M3 are almost same and henceforth all the simulations shall be performed on M2. The mesh of M2 is shown in figure 5.

The turbulence model chosen for the simulations is SST k-ω. Firstly the simulations for equilibrium flows have been done and then the results of the equilibrium simulations are used as initial condition for non-equilibrium simulation. The temperature of both phases is assumed constant in equilibrium calculation where as in non-equilibrium calculation same temperature is not considered. It is assured that the solution presented in the current work was converged to normalized RMS residuals of the order of 10-5 or lower. This convergence criterion is maintained for all the simulations.

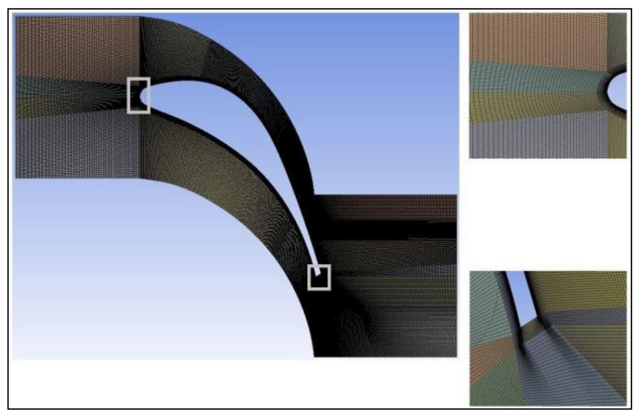

Figure 4: Grid Independency

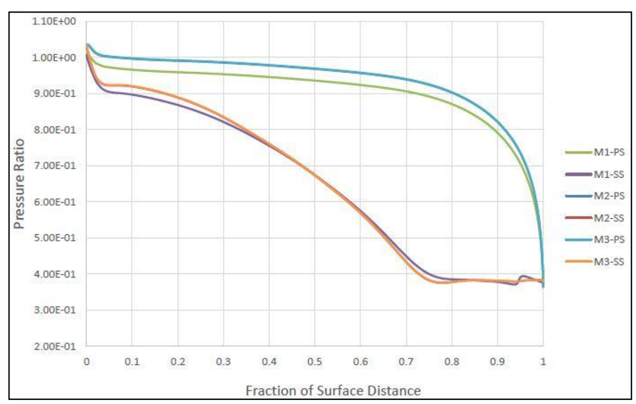

Figure 5: Computational Grid (M2)

The result validation is shown in figure 6. It is observed that droplet size has negligible effect on pressure distribution.

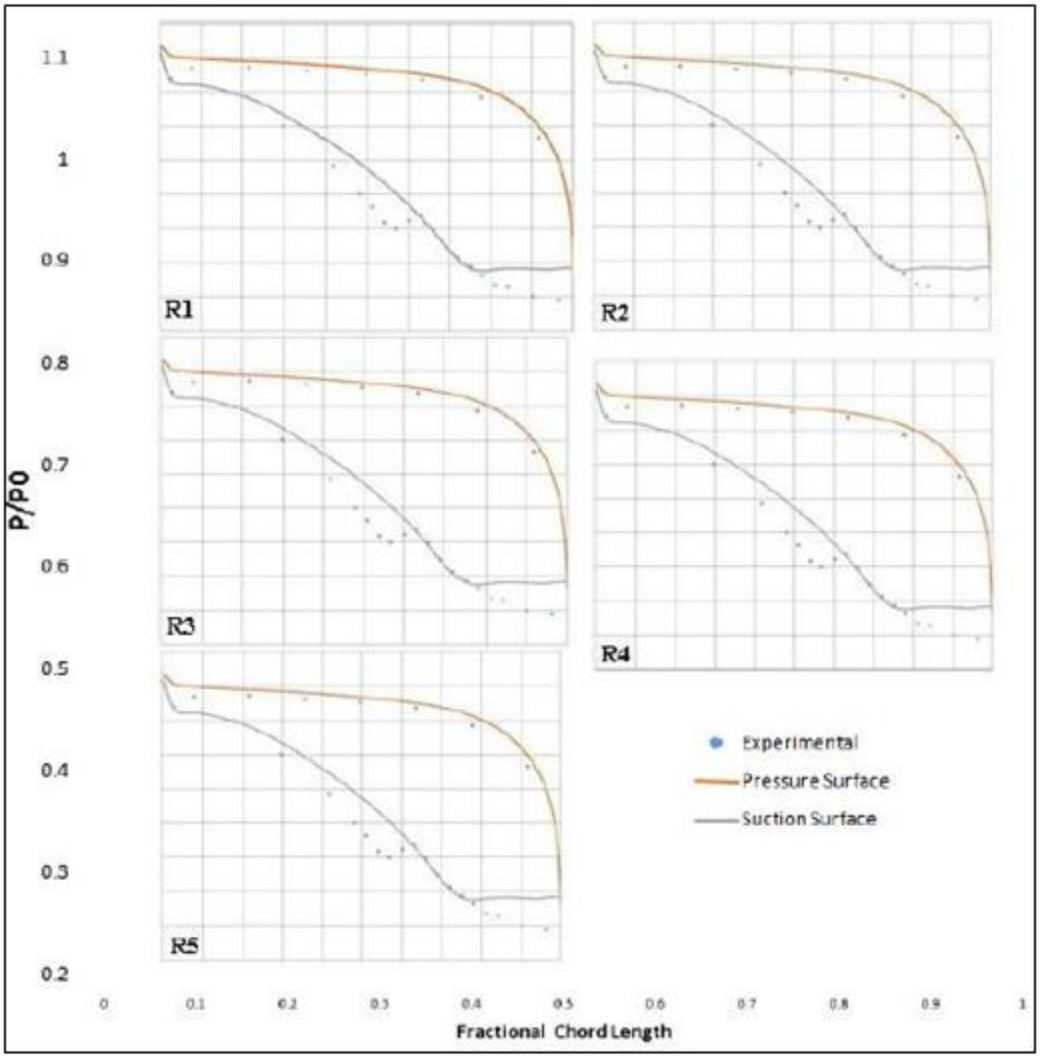

Figure 6: Blade Surface Pressure Distribution

The pressure distribution according to the calculation has certain amount of deviation from the experimental result. This is because condensation of primary droplets was enough to arrest excessive departures from equilibrium and therefore the secondary nucleation was less intense and continued for a longer period. Moreover, the calculation does not consider slip between vapour and water droplets although there is considerable slip for larger droplets with vapour phase.

Figure 7(a) and 7(b) shows fractional diffusion deposition for pressure and suction surface respectively.

The deposition is maximum for minimum droplet size and vice versa. Increase beyond one micron droplet size does not change the deposition considerably. The deposition near the trailing edge of pressure surface and nearly after 25% of blade surface distance from leading edge for suction surface suddenly decreases due to the change of regime from eddy-diffusion to inertia-moderated. It is noted that blade shape has immense effect on deposition and thus can never be represented with single fractional diffusion [20] deposition value as it was the case in past with considerably simple blade profile.

Fractional inertial deposition on both pressure and suction surface is depicted in figure 8 (a) and (b). As expected, the inertial deposition increases as droplet size increases. It is also noted that deposition saturates beyond one micron, i.e. deposition does not change considerably after one micron.

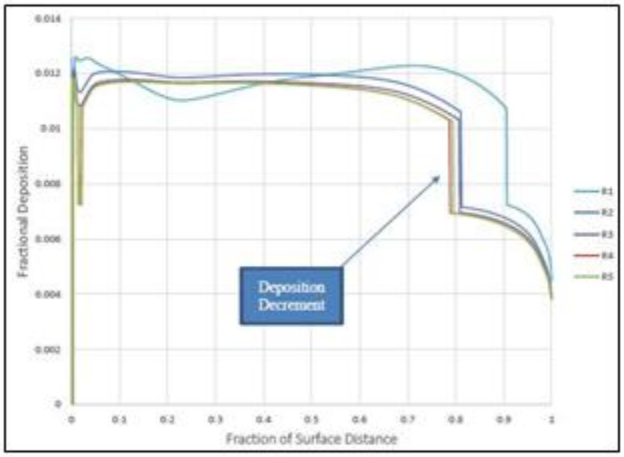

Figure 7(a): Fractional diffusion deposition on pressure surface

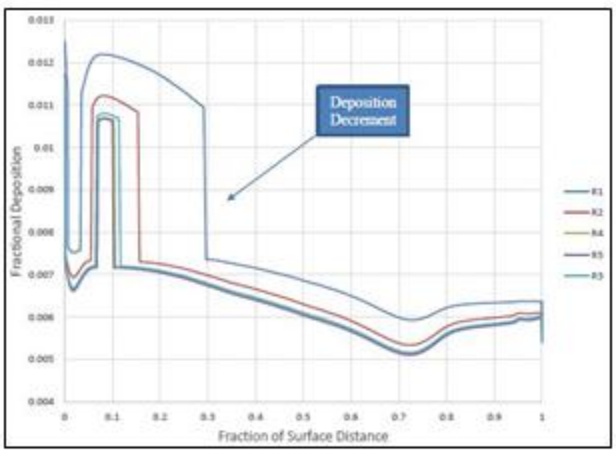

Figure 7(b): Fractional diffusion deposition on suction surface.

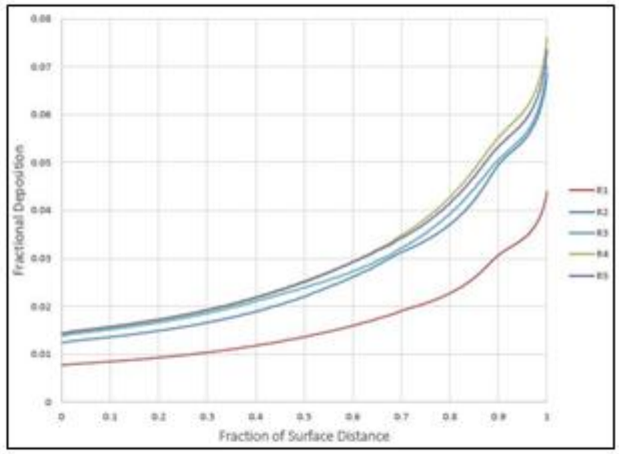

Figure 8(a): Fractional inertial deposition on pressure surface.

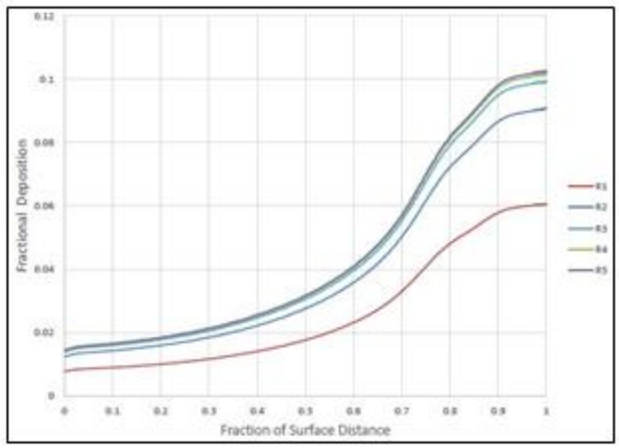

Figure 8(b): Fractional inertial deposition on suction surface

The fractional inertial deposition increases from leading to trailing edge mainly due to two reasons, firstly more number of droplets is formed as steam loses its energy while travelling through blade passage and secondly due to complex blade shape the vapour has to take sharp path which the larger droplet cannot follow and results in deposition.

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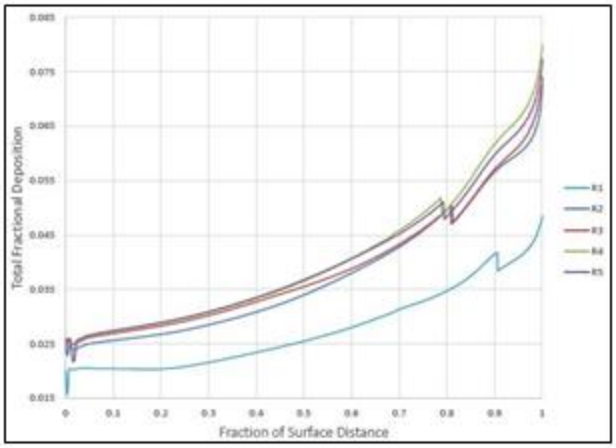

Figure 9 (a): Fractional total deposition on pressure surface.

Figure 9(a) and 9(b) describes total fractional deposition on the pressure surface and suction surface respectively. Total fractional deposition is obtained by the summation of fractional diffusion and fractional inertial deposition. The plots clearly show the effect of droplet size and blade shape. In the past with considerable simple blade profile it was the practice to design the blades with single fractional depositional value. But with the advent of CFD and advanced design, blade profiles have become complex over years and so single fractional depositional modelling [20, 21] is not enough for the entire blade profile.

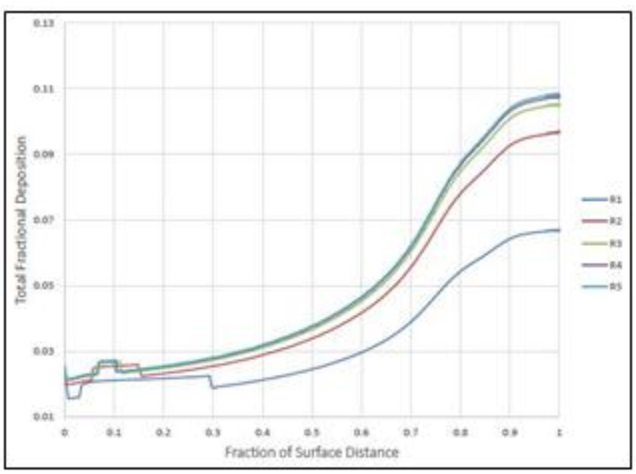

Figure 9(b) : Fractional total deposition on suction surface.

V. CONCLUSIONS

The study focuses mainly on the effect of droplet size and blade shape on fog droplet deposition with reference to previous experimental result and analysing the same with CFD modelling. It was seen that droplet with smaller radius are most efficient for diffusion deposition as it is a boundary layer phenomenon and droplet with small size can easily diffuse through boundary layer, whereas for larger droplets diffusion through boundary layer becomes difficult. Larger droplets effectively deposit by inertial deposition. Blade shape defines the path between blade passages. With complex blade shape path too becomes complex. The vapour has to traverse through complex path pattern and in doing so steam loses its energy by the creation of large number of droplets in due course of its journey which are ultimately deposited on the blades.

There are scopes of further work related to loss or exergy analysis of the same and the effect on deposition for different angle of attack can be important continuation of the present work in future.

REFERENCES

[1] Crane, R. 2004, Droplet deposition in steam turbines. In Proc. Inst. Mech. Eng. Part C, 218, 859-870.

[2] Bakhtar, F.,Ebrahimi, M., Bamkole, B., 1995. "On the performance of a cascade of turbine rotor tip section blading in nucleating steam, Proc. Inst. Mech. Eng.: J. Mech. Eng. Sci., Vol. 209, pp.169–177.

[3] Bakhtar, F., Ebrahimi, M., and Webb, R., 1995. "On the performance of a cascade of turbine rotor tip section blading in nucleating steam, part 1: surface pressure distributions". Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci., Vol.209, pp. 115–124.

[4] White, A.J.,Young,J.B., Walters, P.T.,1996;"Experimental validation of condensing flow theory for a stationary cascade of steam turbine blade". Philos. Trans. Roy. Soc. London., Vol.A354, pp. 59–88.

[5] White, A. J., and Young, J. B., 1993. "Time-marching method for the prediction of two-dimensional unsteady flows of condensing steam". AIAA J. Propulsion and Power, Vol.9 (4), pp. 579–587.

[6] Bakhtar, F., Mahpeykar, M.R.,Abbas, K. K., 1995. "An investigation of nucleating flows of steam in a cascade of turbine blading-theoretical treatment". ASME J. Fluids Eng., Vol.117, pp. 138–144.

[7] Gerber, A.G., and Kermani, M.J., 2004. "A pressure based Eulerian-Eulerian multi-phase model for non-equilibrium condensation in transonic steam flow". Int. J. Heat Mass Transfer,Vol.44, pp. 2217–2231.

[8] Senoo, S., and Shikano, Y., 2002. "Non-equilibrium homogeneously condensing flow analyses as design tools for steam turbines". In ASME FEDSM'2002, Montreal, July 14-18, FEDSM2002-31191.

[9] Starzmann, J., Kaluza, P., Casey, M. V., and Sieverding, F., 2013. "On kinematic relaxation and deposition of water droplets in the last stages of low pressure steam turbines". InProc.ASMETurboExpo, GT2013-95179, SanAntonio, Texas, USA, June 3-7, pp. 1-12.

[10] Friedlander, S. K., Johnstone, H. F.,1957, Deposition of suspended particles from turbulent gas streams, Ind. Eng. Chem., Vol. 49, 1151-1156.

[11] Montgomery, T. L., and Corn, M., Aerosol deposition in a pipe with turbulent airflow, J. Aerosol Science, Vol 40, 1970, 185-213.

[12] Liu, B. Y. H., and Agarwal, J. K., Experimental observation of aerosol deposition in turbulent flow, J. Aerosol Science , Vol.-5, 1974, 145-155.

[13] Cleaver, J. W., and Yates, B., A sub-layer model for the deposition of particles from a turbulent flow, Chem. Eng. Sci., Vol. 30, 1975, 983-992.

[14] Reeks, M. W., and Skyrme, G., The dependence of particles deposition velocity on particles inertia in turbulent pipe flow, J. Aerosol Science, Vol. 7, 1976, 485-495

[15] El-Shobokshy, M. S., and Ismail, I. A., Deposition of aerosol particles from turbulent flow onto rough pipe wall, Atmospheric Environment, Vol. 14, 1980, 297-304

[16] Wood, N. B., 1981, A simple method for the calculation of turbulent deposition to smooth and rough surfaces, J. Aerosol Science, Vol 12, 257-290

[17] Parker, G. J., Lee, P., 1972, Studies of deposition of submicron particles on turbine blades, Proc. Inst. Mech. Engrs, Vol.186, 519-26

[18] Parker, G. J., and Ryley, D. J., Equipment and techniques for studying the deposition of submicron particles of turbine blades, Proc. Inst. Mech. Engnrs., Vol. 184, Part 3C, 1969-70, 43-51.

[19] Gyarmathy, G., Bases of a Theory for Wet Steam Turbines, Bull. 6. Inst. for thermal turbomachines, Federal Technical University, Zurich, CEGB Translation T-781, 1962.

[20] Yau, K.; J. Young 1987, The deposition of fog droplets on steam turbine blades by turbulent diffusion. Journal of turbomachinery , 109, 429-435.

[21] Young, J.; K. Yau. 1988, The inertial deposition of fog droplets on steam turbine blades. Journal of turbomachinery , 110, 155-162.