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Estimation of Heat Transfer Coefficient using CFD techniques on a solid Cylinder

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ABSTRACT

Heat transfer coefficient (HTC) is one of the essential parameters to evaluate the thermal stresses in the steam turbine components like rotor, casing, etc, using finite element methods. HTC is used to predict the local temperature distributions and the induced stresses in the component with finite element methods. HTC depends on number of variables like thermal properties of fluid, hydrodynamic characteristics of the flow regime and boundary conditions. There are numerous empirical equations available in literature to calculate HTC in different fluids, flow regimes, geometries and under different thermodynamic conditions. However, it is necessary to use these equations carefully, as they are defined for a specific range of parameters and their applicability to complicated geometries of steam turbine components needs to be verified. The inaccuracy in HTC values leads to incorrect estimation of the local temperature distributions and the induced stresses. To overcome this uncertainty, an empirical correlation is formulated to estimate HTC based on Conjugate Heat Transfer Study on a solid cylinder which is close representation of typical steam turbine casing. The results of the proposed study are within acceptable limit of ±25% compared with available correlations for the range of Reynolds Number 1.5×10^5 to 7.55×10^5.

Keywords: Heat Transfer coefficient, Nusselt Number, Heat Transfer, CFD, Steam Turbine Casing, Cylinder

Abbreviations:

r = Radius
L =Length
k = Thermal conductivity of metal
T = Temperature
Q = Heat Transfer
1 & 2 = Subscript indicates to inner surface and outer surface respectively
A = 2ΠrL (heat transfer area at location r)
T_∞ = Approach/bulk fluid temperature.
in& out = Indicates inlet and outlet location
m = Mass flow rate of fluid
Cp = Heat capacity of the fluid
ρ = Fluid density
V = Fluid velocity
D_h = Hydraulic diameter
μ = Fluid Dynamic viscosity
k_f = Thermal conductivity of fluid
h = Heat Transfer Co-efficient (HTC)
Re = Reynolds number ($\rho V D_h/\mu$)
Pr = Prandtl number ($\mu C_p/k_f$)
$\delta\rho/\delta t$ = The rate of increase of density in the control volume
$\nabla.(\rho V)$ =The rate of mass flux passing out of control volume
π_{ij} = Stress tensor.
t = Time

1. INTRODUCTION

Heat transfer coefficient is a quantitative characteristic of convective heat transfer between a fluid medium and the surface flowed over by the fluid. It is the proportionality coefficient between the heat flux and the thermodynamic driving force for the flow of heat i.e., the temperature difference. The magnitude of heat transfer coefficient depends on many parameters such as flow geometry, flow rate, flow condition and fluid type. The dependence of HTC on these parameters can be represented by dimensionless numbers such as Reynold's number (Re), Nusselt number (Nu), Prandtl number (Pr) as per the Reynolds analogy. The estimate HTC using the correlations are valid for simple geometries and specific range of parameters. The applicability of these correlations needs to be verified for complicated geometries of steam turbine components. Experiment study on heat transfer on a solid cylinder (D=150mm and L=300mm) is carried out by Roland Wiberg,et. al. [1] to estimate local Nusselt number for Re number of 8.9×10^4 to 6.17×10^5; estimation of Nu number through heat transfer is carried out on rotating cylinders by Bari Ozerdem[2], K.S. BALL, et. al [3] and inside a rotating cylinder by S. Seghir-Ouali, et. al [4] through experiment and verified through theoretical correlation where maximum Re number of 4.33x10^5. Analytical approach on 2D system for approximate solution from an isothermal rotating cylinder is followed by Abdullah Abbas Kendoush [5] and verified the results with available experimental data. The results of research work as mentioned above are verified with existing correlations which are generated from several experimental investigations as shown in Table 1.

Table 1 Correlations for estimation of Nusselt Number from literature

Author	Equation	Remark & Referance
Anderson & Saunders	$\overline{Nu} = 0.1\ \mathrm{Re}_r^{\ 2/3}$	Analogy solution
Etemad	$\overline{Nu} = 0.076\ \mathrm{Re}_r^{\ 0.7}$	$8000 \le \mathrm{Re}_r \ge 65400$
Etemad	$\overline{Nu} = 0.11\ [(0.5\ \mathrm{Re}_r^{\ 2} + \mathrm{Gr})\ \mathrm{Pr}]^{\ 0.35}$	$1000 \le \mathrm{Re}_r \ge 8000$
Dropkin & Carmi	$\overline{Nu} = 0.073\ \mathrm{Re}_r^{\ 2/3}$	$15000 \le \mathrm{Re}_r \ge 433000$
Dropkin & Carmi	$\overline{Nu} = 0.095(0.5\ \mathrm{Re}_r^{\ 2} + \mathrm{Gr})^{\ 0.35}$	$1000 \le \mathrm{Re}_r \ge 15000$
Kays & Bjorklund	$\overline{Nu} = \dfrac{Re\,Pr\,\sqrt{(f/2)}}{5\,Pr + 5\,ln(3\,Pr + 1) + \left[1/\sqrt{(f/2)}\right] - 12}$	Analogy solution
Becker	$\overline{Nu} = 0.119\ \mathrm{Re}_r^{\ 2/3}$	$800 \le \mathrm{Re}_r \ge 100000$
Shimada et al.	$\overline{Nu} = 0.046\ \mathrm{Re}_r^{\ 0.7}\ (1+8\ \mathrm{Gr} / \mathrm{Re}_r^{\ 2})^{\ 0.95}$	$300 \le \mathrm{Re}_r \ge 3000$
Özerdem	$\overline{Nu} = 0.318\ \mathrm{Re}_r^{\ 0.571}$	$2000 \le \mathrm{Re}_r \ge 40000$, this study

Most of the research worksareon rotating components inside air flow media.The authors are more focused on the effect on Reynolds number as the secondary flow plays a major role on heat transfer and Prandtl number is constant (i.e. 0.72) for air medium.An analytical formula is used to estimate HTC and verified with experiment by Adinarayana [6] on industrial steam turbine rotor. Effect of axial and rotational flow for estimation of Reynolds number (max Re 5x10^4) and fluid property dependent Prandtl number is considered in the analytical formula.

The focus of the present study is to estimate heat transfer coefficient using CFD technique for four different combinations of flow and thermal conditions on annulus passage between stationary solid cylinders which is a close representation of a steam turbine casing.In this case, the effect of Reynolds number and Prandtl number is considered for accurate estimation of heat transfer phenomenon on steam flow medium. Finally a correlation is formulated to estimate Nu number for similar kind of geometry where Reynolds number varies between 1.5x10^5 to 7.55x10^5. However, an empirical correlation is available in ESDU (Engineering Science Data Unit) standard [7] to estimate Nu number as per the present study conditions. The Nu numbers predicted by CFD simulation are compared with empirical calculations and the results are presented. CFD study on turbulent flow (max Re 2.5 x10^4) heat transfer in tubular exchanger is carried out by Hesham G. Ibrahim[8] and the results are verified with experiment. The author is also presented the empirical correlation to estimate the Nusselt number and deviation between experiment, Reynolds analogy and CFD results of ±25% is accepted. The same acceptable limit is also mentioned in Heat and Mass transfer text book [9] depending on the condition of flow and geometry of the fluid passage.

2. ANALYTICAL SOLUTION

Steady state heat conduction through a steel cylinder, as shown in Fig.1, is considered for the study. To model steady state condition, constant heat source in the form of heat flux is applied on the cylinder inner surface and cooler steam flow is passed over the outer surface of the cylinder. Heat is continuously lost to the outer surface of the cylinder through the wall of the cylinder. It is assumed that the heat transfer through the cylinder is normal to the cylinder surface and no significant heat transfer takes place in the cylinder in other directions. The temperature of the cylinder is dependent on heat transfer in one direction only (the radial r-direction).

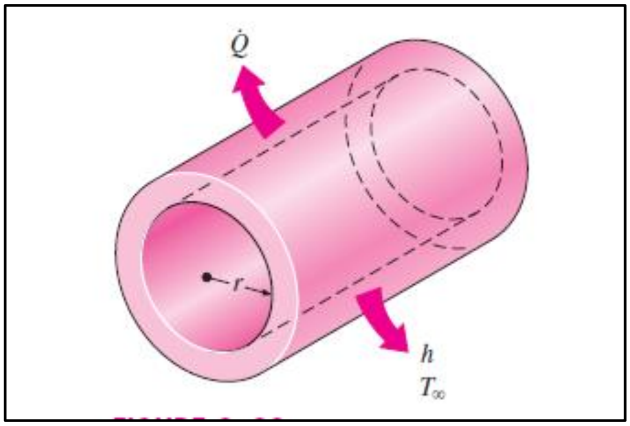

Figure 1 Representation of Cylinder for heat flow

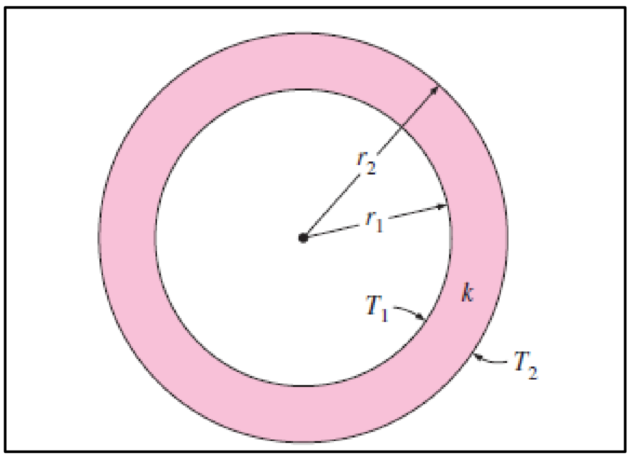

Figure 2 Cylinder C/S and thermal representation

In steady state operation, there is no change in the temperature of the cylinder with time at any point. Therefore, the rate of heat transfer into the cylinder must be equal to the rate of heat transfer out of it, i.e., Heat transfer through the cylinder is constant (Q).

Fig.2 shows the cross section of cylinder where the two surfaces of the cylindrical layer are maintained at temperatures T_1 and T_2. There is no heat generation in the layer and the thermal conductivity (k) is constant. Energy transfer from solid to fluid is taken place through the solid- fluid interface. Cylinder length (L) and cylinder radius (r_1 and r_2) are constant for all the cases in the study. Heat (Q) value is constant for three cases and double for a case. Cross sectional area on annulus flow passage and flow velocity is also varied on the four cases.

Convective heat transfer is taken place when there is a temperature difference between the heated surface and the moving fluid. This phenomenon is referred to as the thermal boundary layer that causes heat transfer from the surface. In addition to the thermal boundary layer, there is also a velocity boundary layer due to the friction induced between the surface and the fluid as the result of the fluid viscosity. The combination of the thermal and viscous boundary layers governs the heat transfer from the surface. Fig.3 shows velocity boundary layer growth (δ) that starts from the leading edge of the plate. The thermal boundary layer (δ_t) starts after a distance (ξ) from where the temperature of the plate changes from fluid temperature to a different temperature (T_2), causing convection heat transfer.Heat transfer co-efficient "h" is generally defined as:

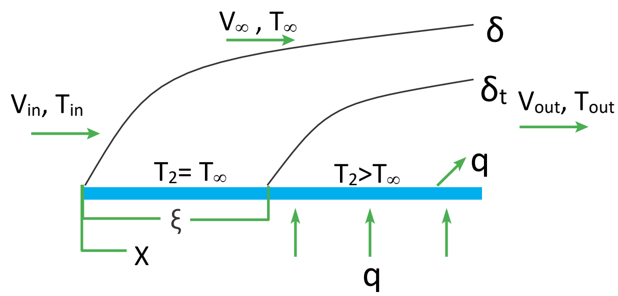

Figure 3 Velocity and thermal boundary layer growth on a heated flat plate

$$h = \frac{Q}{A(T_2 - T_\infty)} \quad \text{........ (1)}$$

To estimate the heat transfer co-efficient from eq (1), metal surface temperature (T_2) and bulk fluid temperature (T_∞) is required along with the total heat and the surface area. Bulk fluid temperature (T_∞) will be varied with difference of heat transfer from solid to fluid. Average temperature of inlet to outlet of cooling fluid is used as bulk fluid temperature (T_∞) in the study to capture the heat transfer from solid to fluid.

$$T_\infty = \frac{(T_{in} + T_{out})}{2} \quad \text{------- (2)}$$

Outer metal surface temperature (T_2), fluid inlet and outlet temperatures (T_{in} and T_{out}) are taken from Conjugate Heat Transfer Study using CFD techniques for estimation of heat transfer coefficient using Eq. (1). Non-dimensional parameter Nu Number is computed from the heat transfer coefficient estimated from CFD study using eq. (3). Subsequently, an empiricalcorrelationsuited for annulus flow geometry is formulatedbased on the present case studies using non-dimensional parameters of Reynolds number and Prandtl Number. The proposed empirical correlation is shown in equation (4).

$$Nu = \frac{h\, D_h}{k_f} \quad \text{-------- (3)}$$

$$Nu = 0.0216 Re^{0.8} Pr^{1/3} \quad \text{-------- (4)}$$

The estimated Nusselt Number from CFD study is compared with the correlationsformulated in present study, the correlations mentioned in Table 1 and ESDU standard.

3. CFD SIMULATION

A hollow solid cylinder, which is same as mentioned in theory part,is taken up for CFD simulation. The cylinder is simplified representation of inner casing for a typical utility steam turbine.Superheated steam is considered as fluid medium for CFD simulation.Steam is made to flow over the cylinder through hollow passageformed between solid cylinder outer surface and inner surface of the outer casing.Inner surface of the solid cylinder is treated as the tip section of bladed flow path where heat source boundary condition is applied for CFD simulation. Fluid-solid interface is applied between outer surface of solid cylinder and the inner surface of fluid domain. CFD model for the Conjugate Heat Transfer (CHT) analysis is shown in Fig. 4. Conjugate heat transfer refers to the ability to compute conduction of heat through solids, coupled with convective heat transfer in a fluid. Cylinder outer surface temperature, Cylinder outer surface area, heat transfer to fluid and bulk fluid temperature are used to compute heat transfer coefficient from the CFD simulation results.There are total 4 cases carried out on same cylinder geometry with different annulus flow passage, heat source and flow velocity conditions. The geometry information and flow conditions for the four cases are shown in Table 2.

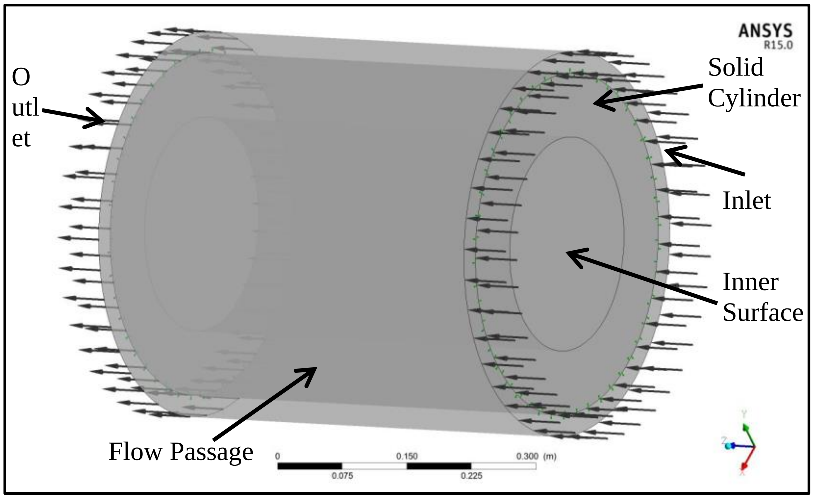

Figure 4 CFD model for Conjugate Heat Transfer study

Objective of case2 and Case 3 is to study the impact of fluid geometry and fluid flow over the cylinder to capture the variation of heat transfer phenomenon compare to case 1. Case 4 is to study the impact of fluid velocity on heat transfer compare to case 1.

CFD theory: CFD is a modeling technique that breaks down the governing equations (continuity, momentum and energy)for fluid flow in to simpler forms that can be solved using Numerical techniques. Continuity, momentum and energy equations are solved in the fluid domain and only energy equation is solved on the solid domain in Conjugate Heat Transfer analysis.

Continuity Equation:
The continuity equation in partial differential equation form is given by,

$$\delta\rho/\delta t + \nabla.(\rho V)=0 \qquad \text{---------- (5)}$$

Momentum Equation:
Newton's Second Law applied to a fluid passing through an infinitesimal, fixed control volume yields the following momentum equation:

$$\delta/\delta t(\rho v)+\nabla.\rho V\ V=\rho f + \nabla.\pi ij \qquad \text{---------- (6)}$$

The first term {$\delta/\delta t(\rho v)$} represents rate of increase of momentum per unit volume. The second term ($\nabla.\rho V\ V$) represents the rate of momentum lost by convection through the control surface. Right hand side equation shows the first term (ρf,) as the body force per unit volume, while the second term ($\nabla.\pi ij$) represents the surface force per unit volume.

Energy Equation:

The first law of thermodynamics is applied to a fluid passing through an infinitesimal; fixed control volume yields the following energy equation in terms of enthalpy.

$$\rho(De/Dt) = Dp/Dt + \delta Q/\delta t - \nabla.q + \phi \qquad \text{--------- (7)}$$

The term {ρ(De/Dt)} in the left hand side is the rate of change of energy inside the fluid element. Right hand side, first two terms (Dp/Dt +δQ/δt) are the rate of work done on element due to body and surface forces; third term (∇.q) is net flux of heat in to element. The last term (ϕ) on the right hand side is known as dissipation function and represents the rate at which mechanical energy is expended in the process of deformation of the fluid due to viscosity.

Total heat transfer across the metal and from metal to fluid through fluid-solid interface location is calculated by numerical techniques in CHT analysis using eq. (7). The CFD study is carried out using ANSYS CFX code. The metal temperature on the cylinder surface and fluid temperature at inlet and outlet estimated through numerical techniques is used in eq. (1) and eq. (2) to estimate HTC.

4. RESULTS AND DISCUSSION

Temperature distribution on the solid cylinder as well as the annulus flow passage is calculated through Conjugate Heat Transfer study using CFD techniques. Heat transfer coefficient is calculated by using eq. (1) and eq. (2) form the CHT study results. Subsequently, non-dimensional parameter Nu Number is estimated from eq. (3) using heat transfer coefficient estimated through CFD study. The properties of steam like thermal conductivity, density, dynamic viscosity are taken from steam table using the flow parameters mentioned in Table 2. The fluid properties are used for calculation of non-dimensional parameters like Reynolds number (Re) and Prandtl Number (Pr). The non-dimensional parameters are used in eq. (4) to calculate of Nu number for all four cases.

Table 2 Geometry and Boundary Condition data for the Study

		Case 1	**Case 2**	**Case 3**	**Case 4**
Inlet	Velocity	V	V	V	2V
	Temperature	T	T	T	T
Outlet	Pressure	P	P	P	P
Cylinder Inner radius		r1	r1	r1	r1
Cylinder Outer radius		r2 (1.6r1)	r2 (1.6r1)	r2 (1.6r1)	r2 (1.6r1)
Fluid chamber radius		1.125 r2	1.05 r2	1.05 r2	1.125 r2
Heat at inner surface		Q	Q	2Q	Q

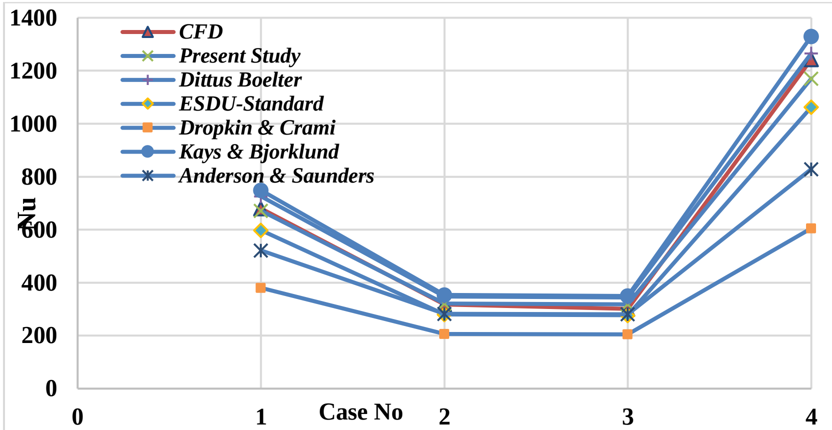

Figure 5 Comparison of Nusselt Number betweenCFD study and empirical correlations

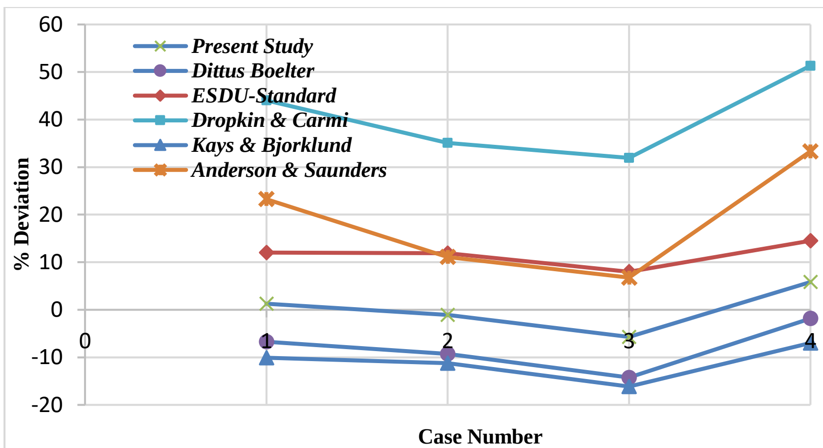

Figure 6 %Deviation of Nusselt number with respect to CFD results

There are numerous empirical equations available in literature as shown in Table 1 to calculate Nu number for estimation of Heat Transfer Coefficient in different fluids, flow regimes, geometries and under different thermodynamic conditions. Dropkin & Carmi, Kays & Bjorklund and Anderson & Saunders correlation mentioned in Table 1 is applicable for the range of Reynolds number between $1.5x10^5$ to $7.55x10^5$proposed in the present study. Comparison of Nu Number between CFD study results and all empirical correlations for four cases is shown in Fig.5. The deviation of the correlation estimated HTC with respect to CFD study results is shown in Fig. 6. The deviation of Nu Number for formulated correlation in the present study, DittusBoelter, ESDU standard, Kays & Bjorklun and Anderson & Saunders formulation is within acceptable limit of 25% with respect to CFD study results.

The maximum variation of Nu number is 5.7% in empirical correlation formulated in the present study is lowest compared to other correlations for first three cases and DittusBoelter correlation is estimated lower deviation (1.8%) of Nu numberfor case 4.Therefore, the correlation formulated in the present study can be used for estimation of heat transfer coefficientfor complex geometry like steam turbine casing before detailed 3D CFD study. However, it is preferable to validate heat transfer coefficientcomputed from CFD analysis with experimental study.

5. CONCLUSION

Conjugate Heat Transfer analysis is carried out on the solid cylinder using CFD techniques and the Nu numbercomputed by CFD simulation results are in agreement with theoretical calculation. Maximum deviation of 5.8% is observedfor empirical correlation formulation in present studywith respect to Nu number calculated fromCFD simulation results. The deviation is well within the acceptable range and may nothave significant impact on structural design finalization. Empirical correlation formulated in present studycan be used to estimate heat transfer coefficient for complex geometry like steam turbine casing by using proper equivalent radius of the solid and fluid geometry along withfluid properties (density, dynamic viscosity, thermal conductivity, etc).To start with the heat transfer coefficient calculated though the correlationformulated in the present study may be used for stress analysis for complex geometry like steam turbine casing even before the results of detailed 3D CFD analysis are calculated.

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