University Turbine Systems Research (UTSR) Industrial Fellowship Program

Tip-Turn Heat Transfer Correlation

Prepared By:

Kevin Liu
Department of Mechanical Engineering
Texas A&M University
College Station, TX 77843

Prepared For:

Southwest Research Institute (SWRI)
San Antonio, TX 78228

Siemens Power Generation (Siemens Energy)
Orlando, FL 32826

Objective

The objective of this work is to create a heat transfer correlation based on open literature experimental database. The well-correlated curve can be used to predict the heat transfer enhancement inside the internal channel with smooth and ribbed surfaces.

Introduction

Gains in thermodynamic efficiency can be realized by increasing the turbine inlet temperatures. Since modern turbine inlet temperatures exceed the melting point of the constituent superalloys, it is necessary to provide an aggressive cooling system. From **Figure 1,** it is seen that different heat transfer enhancement techniques are used for different portions of the gas turbine blade. In the internal cooling channel jet impingement cooling is used at the leading edge of the blade. In the mid portions of the blade, angled ribs are used to break the boundary layer and create secondary flows. At the trailing edge of the blade, pin fin cooling is used.

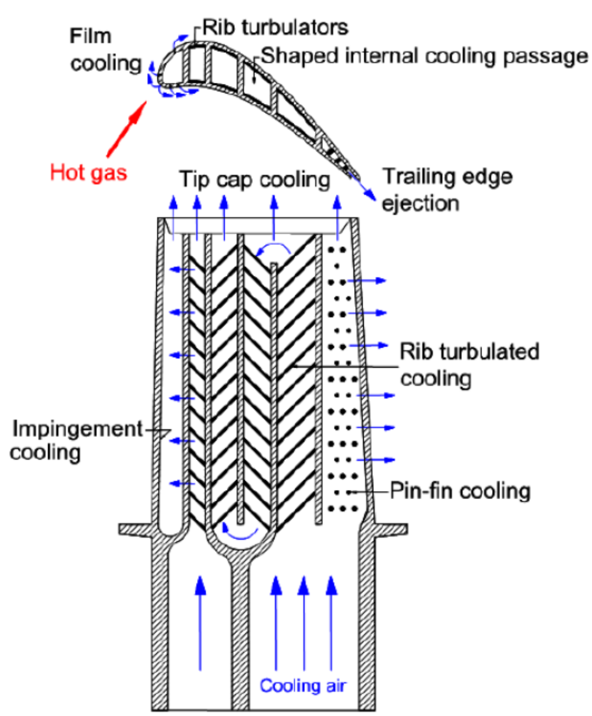

Figure 1 Typical internal cooling of a gas turbine blade

The idea of internal cooling is to circulate compressed air in the multi-pass flow channels inside the blade structure. The internal cooling of the gas turbine blade is influenced by the channel aspect ratio, rotational and flowing parameters.

The cross-section of the internal cooling channels varies from the leading edge to the trailing edge of the gas turbine blade, as shown in **Figure 2**. Different geometrical cross sections are used to simulate the internal channel at different location.

The flow field is strongly affected by rotation and so is heat transfer, this can be attributed to the effect of Coriolis and rotation induced buoyancy forces. For radially outward flow, the Coriolis force induces secondary flows in a plane perpendicular to the mainstream flow.

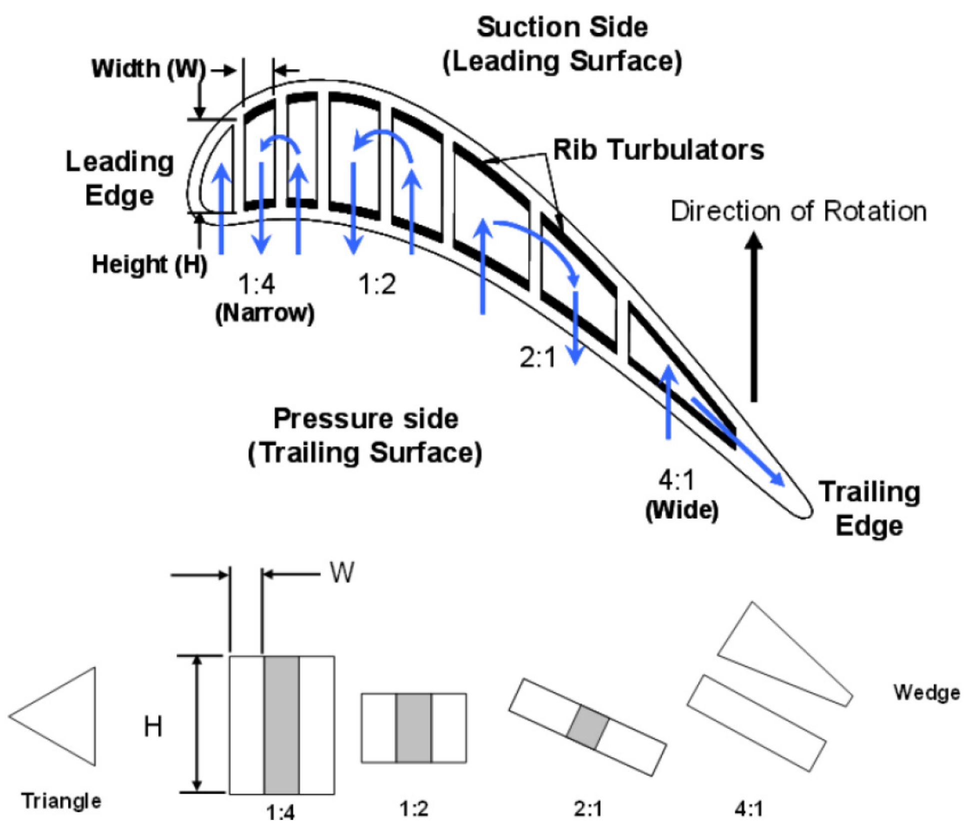

Figure 2 Geometries used in the simulation of gas turbine blade internal cooling channels

A sharp 180° turn is used to connect the first pass channel to the second pass channel in a gas turbine blade. Secondary flows are generated in the turn region due to the turn geometry. As the result, the secondary flow enhances the heat transfer.

Experimental Data Reduction and Analysis

Tip-Turn project is a program designed to investigate the heat transfer at tip-turn region of a U-shaped or multi-channel serpentine passage. The heat transfer coefficient data is found using transient liquid crystal or regional average copper plate measurements. The investigations focused on the influence of tip-to-web distance, rotating effect, and effect of pin-fins in the tip-turn region.

In the following report, the heat transfer analysis is demonstrated by using data collected from open literatures. There are several important parameters used for quantifying the heat transfer enhancement, geometry of internal cooling channel, effects of Coriolis force, and rotation induced buoyancy forces.

Nusselt number is the ratio of convective to conductive heat transfer across the boundary and is given as:

$$Nu = \frac{hD_h}{k} \tag{1}$$

The effect of rotation is evaluated by the rotation number (Ro) which is the ratio of the Coriolis force to the bulk inertia force as shown in Equation (2).

$$Ro = \frac{\Omega D_h}{U_b} \tag{2}$$

The combine effect of rotation and temperature is evaluated by the local buoyancy parameter. The local buoyancy parameter is defined as:

$$Bo_x = \left(\frac{\Delta\rho}{\rho_x}\right)(Ro)^2\left(\frac{R_x}{D_h}\right) \tag{3}$$

This local buoyancy parameter can be re-written by incorporating the measured wall and bulk temperatures and by assuming the fluid to be an ideal gas as shown in Equation (4).

$$Bo_x = \left(\frac{T_{w,x} - T_{b,x}}{T_{w,x}}\right)(Ro)^2\left(\frac{R_x}{D_h}\right) \tag{4}$$

The Dittus-Boelter correlation for fully developed turbulent flow through a smooth stationary pipe is used to provide a basis of comparison, and is given as:

$$Nu_0 = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{5}$$

The Nusselt number ratio is correlated to normalized tip-to-web distance, rotation number and buoyancy parameter with a power-law function as shown in Equation 6 to 9.

$$\frac{Nu}{Nu_{smooth}} = A\cdot\left(\frac{W_{el}}{W_{avg}}\right)^m \tag{6}$$

$$\frac{Nu}{Nu_0} = A\cdot \mathrm{Re}^m \tag{7}$$

$$\frac{Nu}{Nu_{stationary}} = A\cdot Ro^m \tag{8}$$

$$\frac{Nu}{Nu_{stationary}} = A\cdot \mathrm{Re}^m \tag{9}$$

The influence of tip-to-web distance on the heat transfer is shown in **Figure 3**. The results of the measurements show that heat transfer in the bend region increased with decreasing tip wall distance. The heat transfer enhancement (Nu/Nu_{smooth}) can be correlated to normalized tip-to-web distance. The coefficients and exponents that correspond to Equation 6, for the ribbed case and unribbed cases, are shown as:

$$\frac{Nu_{ribbed}}{Nu_{smooth}} = 2.299\left(\frac{W_{el}}{W_{avg}}\right)^{-0.243}$$

$$\frac{Nu_{unribbed}}{Nu_{smooth}} = 2.503\left(\frac{W_{el}}{W_{avg}}\right)^{-0.135}$$

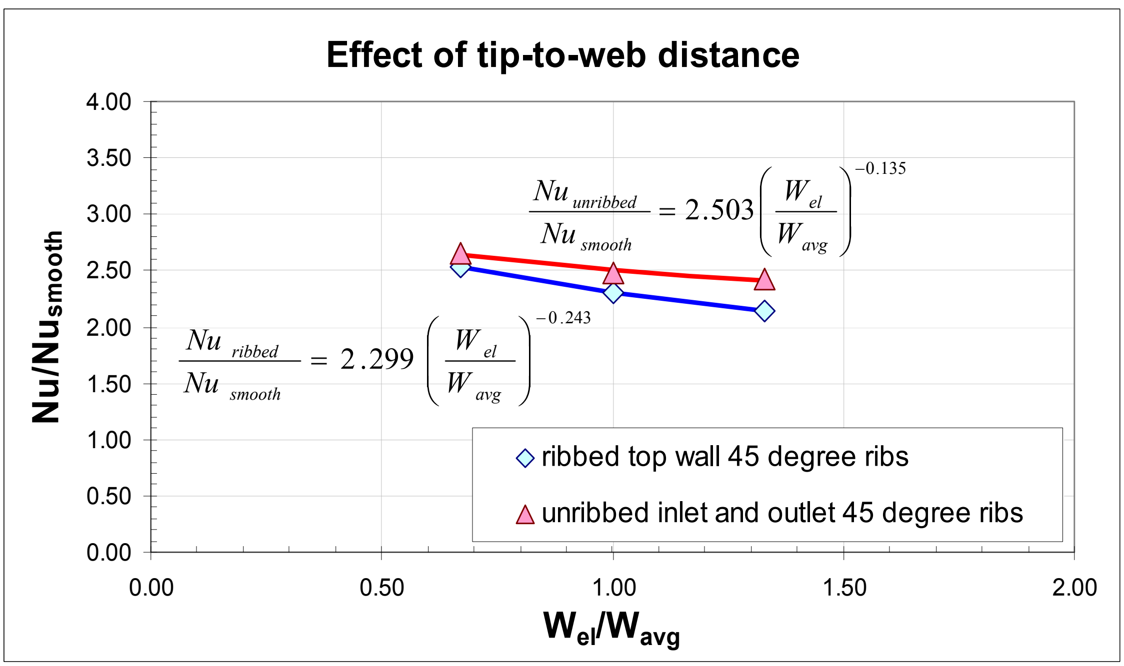

Figure 3 Nu/Nu_{smooth} ratios for all tip-to-web distance (GT2008-51207)

The Nusselt number ratio (Nu/Nu_0) is used to show the heat transfer enhancement relative to fully developed, turbulent heat transfer in a circular tube. This fully developed, turbulent heat transfer can be expressed with the Dittus-Boelter - McAdams correlation for heating. Equation 10 shows this Nusselt number ratio.

$$\frac{Nu}{Nu_0} = \left(\frac{hD_h}{k}\right)\left(\frac{1}{0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}}\right) \tag{10}$$

Figure 12 shows the Nu/Nu_0 ratios as a function of the Reynolds number at stationary test. The correlated function corresponds to Equation 7 is given as:

$$\frac{Nu}{Nu_0} = 807.664 \cdot \mathrm{Re}^{-0.567}$$

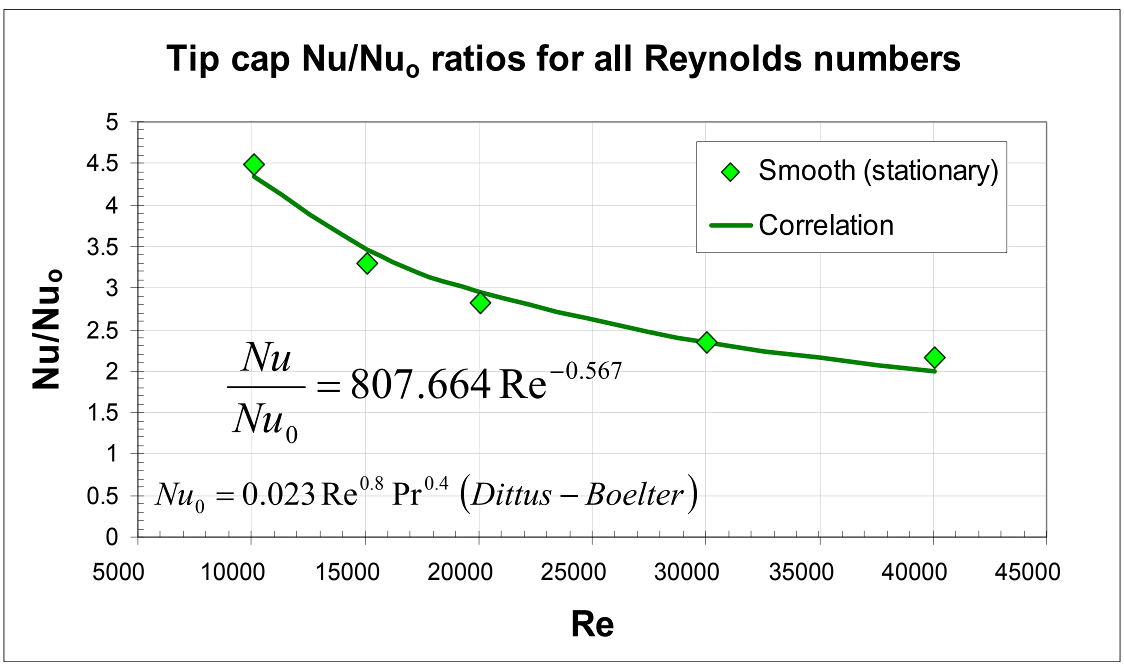

Figure 4 Nu/Nu_0 ratios for all Reynolds numbers (GT2010-22190)

The flow field is strongly affected by rotation and thereby the heat transfer. Compared to a stationary reference frame, rotation will increase heat transfer on the trailing wall and reduce heat transfer on the leading wall with radially outward flow.

Rotation number is a ratio of Coriolis force to the bulk flow inertia force. This non-dimensional parameter is widely used to quantify the effect of rotation in the industry and academia. Heat transfer enhancement due to effect of rotation is represented by the ratio of the rotational Nusselt number to the stationary Nusselt number ($Nu/Nu_{stationary}$). **Figure 5** shows this heat transfer enhancement ($Nu/Nu_{stationary}$) including Reynolds number from 10000 to 40000 and the rotational speed from 0 to 400 rpm.

The correlation functions are:

$$\frac{Nu_{LE}}{Nu_{stationary}} = 1.694 \cdot Ro^{0.14}$$

$$\frac{Nu_{TE}}{Nu_{stationary}} = 0.83 \cdot Ro^{-0.027}$$

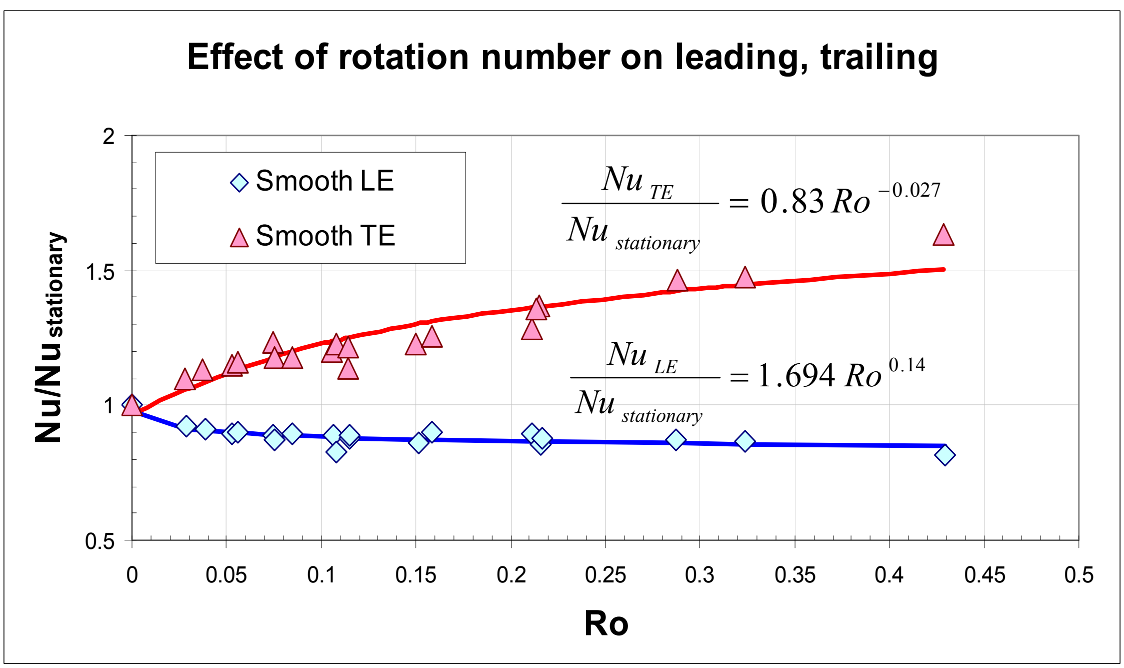

Figure 5 Effect of rotation number on leading, trailing walls (GT2010-22190)

The buoyancy parameter is also a widely used non-dimensional parameter to quantify the effect of rotation inside the gas turbine blade. The buoyancy force due to the centrifugal force and temperature difference is important due to the high rotating speed and large temperature difference in the actual engines. The buoyancy parameter considers all factors affecting the effect of rotation: the density ratio (temperature difference), the rotation number, and the rotating radius.

A Nusselt number ratio of rotating Nusselt number to the stationary Nusselt number ($Nu/Nu_{stationary}$) is presented in order to show the heat transfer enhancement or declination due to rotation as shown in **Figure 6**.

The correlation functions are:

$$\frac{Nu_{LE}}{Nu_{stationary}} = 1.484 \cdot Bo^{0.064} \qquad \frac{Nu_{TE}}{Nu_{stationary}} = 0995 \cdot Bo^{-0.001}$$

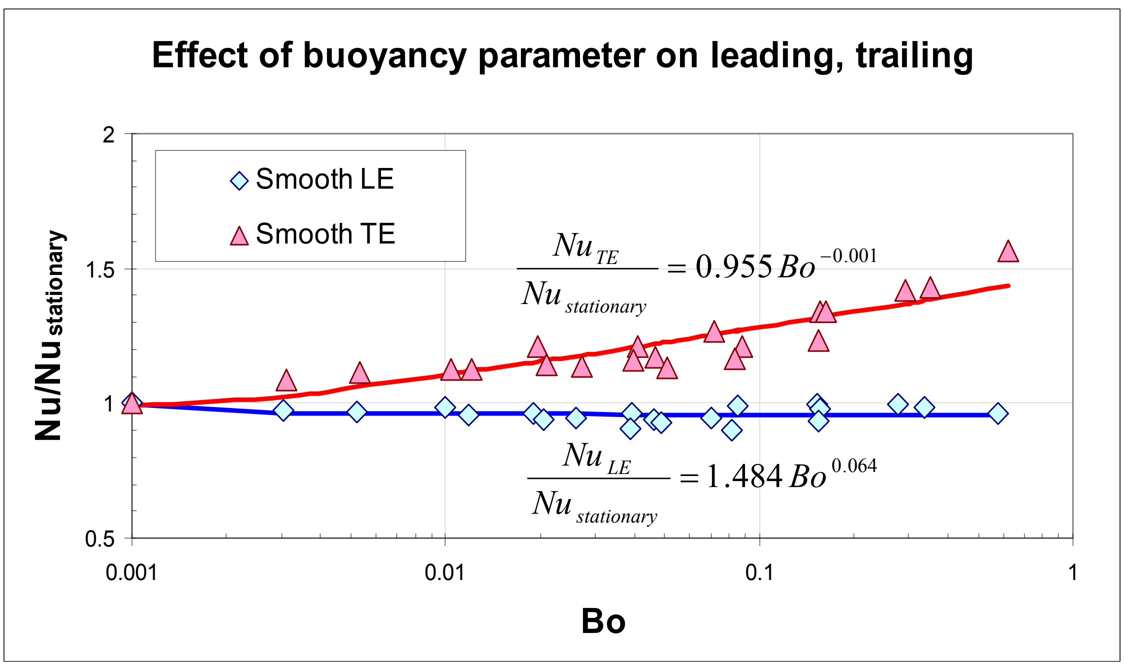

Figure 6 Effect of local buoyancy parameter on leading, trailing walls (GT2010-22190)

Nomenclature

Bo_x	local buoyancy parameter, $(\Delta\rho/\rho)Ro^2(R_x/D_h)$
D_h	channel hydraulic diameter
H	channel height
LE	leading edge, (suction side)
h	heat transfer coefficient
k	thermal conductivity of the coolant
Nu	Nusselt number, $h \cdot D_h/k$
Nu_{smooth}	Nusselt number for a smooth surface
$Nu_{stationay}$	stationary Nusselt number
Nu_0	Nusselt number for fully developed turbulent flow in stationary smooth pipe, $0.023Re^{0.8}Pr^{0.4}$
Pr	Prandtl number of the coolant
R_x	local radius of rotation
Re	Reynolds number, $\rho \cdot U_b \cdot D_h/\mu$
Ro	rotation number, $\Omega \cdot D_h/ U_b$
$T_{w,x}$	local wall temperature
$T_{b,x}$	local coolant bulk temperature
TE	trailing edge, (pressure side)
U_b	bulk velocity in streamwise direction
W	channel width
W_{el}	divider wall-to-tip wall distance
W_{avg}	averaged width of the inlet and exit channels
μ	dynamic viscosity of the coolant
$\rho_{b,x}$	local density of air based on local bulk temperature
$\rho_{w,x}$	local density of air based on local wall temperature
$\Delta\rho/\rho$	local bulk-to-wall density ratio, $(\Delta\rho= \rho_{b,x}- \rho_{w,x})$
Ω	rotational speed

Comments on UTSR Industrial Fellowship

I would like to conclude by expressing my sincere thanks to everyone at Siemens who made my internship both educational and enjoyable. I was always surrounded by intelligent and knowledgeable professionals who were more than willing to share their knowledge on anything with me. The lessons I have learned here will definitely help me through my future academic work and my future career.

I would also like to thank everyone at UTSR for giving me this incredible opportunity to work with Siemens Energy, one of the world's leaders in the design of gas turbines. All of the knowledge that I have learned throughout the 10-week fellowship has really broaden my horizons.