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Sensitivity analysis of freestream turbulence parameters on stagnation region heat transfer using a neural network

Babak Seyedan [a], Chan Y. Ching [b,*]

[a] *Hatch Acres, 1235 North Service Road West, Oakville, Ont., Canada L6M 2W2*
[b] *Department of Mechanical Engineering, McMaster University, Hamilton, Ont., Canada L8S 4L7*

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Abstract

A neural network has been used to predict stagnation region heat transfer in the presence of freestream turbulence. The neural network was trained using data from an experimental study to investigate the influence of freestream turbulence on stagnation region heat transfer. The integral length scale, Reynolds number, all three components of velocity fluctuations and the vorticity field were used to characterize the freestream turbulence. The neural network is able to predict 50% of the test data within ±1%, while the maximum error of any data point is under 3%. A sensitivity analysis of the freestream turbulence parameters on stagnation region heat transfer was performed using the trained neural network. The integral length scale is found to have the least influence on the stagnation line heat transfer, while the normal and spanwise turbulence intensities have the highest influence.
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Keywords: Stagnation region heat transfer; Neural network; Sensitivity analysis

1. Introduction

Stagnation region heat transfer is important in many engineering applications. For example, heat transfer from the combustion gases to the turbine blades in a gas turbine is highest in the stagnation region. Accurate predictions of heat transfer in this region are essential to improve the design of blade cooling systems. However, accurate estimation of the stagnation region heat transfer on turbine blades is difficult due to the complexity of the flow field (Maciejewski and Moffat, 1962; Larsson, 1997; Guo et al., 1998). There have been several experimental studies on the effect of freestream turbulence on stagnation region heat transfer, and correlations between the stagnation region heat transfer and the characteristics of freestream turbulence such as turbulent intensity (u'), integral length scale (λ_x) and Reynolds number (Re_D) have been developed (Lowery and Vachon, 1975; Mehendale et al., 1991; VanFossen et al., 1995). In most cases, however, the correlations are experiment specific since the heat transfer is not only dependent on the turbulence parameters u', λ_x and Re_D, but also on the distinct nature of the turbulence. For example, the combustion gases exiting the combustor tend to be highly anisotropic and well laced with distinct coherent vortical structures. Hence, for more accurate predictions, the correlation models must take into account the distinct nature of the turbulence. This can be achieved by incorporating the rms of all three components of velocity fluctuations (u', v', w') and vorticity (ω_y, ω_z) in addition to λ_x (Oo and Ching, 2001, 2002). The increased number of variables, however, makes it more difficult to obtain accurate correlations and to determine the relative importance of the different parameters on the heat transfer. In this instance, it is difficult to perform a parametric study due to the difficulty of changing a single turbulence parameter while keeping the others fixed. For example, changing the turbulence grid size to increase the turbulence intensity also increases the integral length scale.

* Corresponding author. Tel.: +1 905 525 9140x24998; fax: +1 905 572 7944.
E-mail address: chingcy@mcmaster.ca (C.Y. Ching).

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Nomenclature

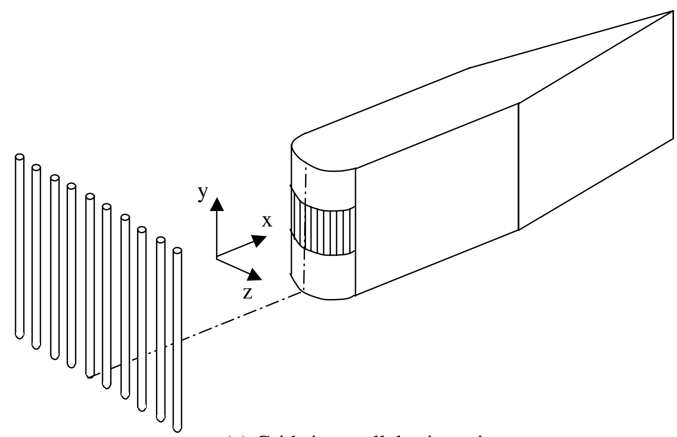
d	diameter of a grid-rod
D	diameter of cylindrical leading edge
Fr	Frossling number $(Nu/\sqrt{Re_D})$
Re_D	Reynolds number based on D
u'	rms of fluctuating velocity component in streamwise direction (m/s)
U	mean freestream velocity (m/s)
v'	rms of fluctuating velocity component in spanwise Y direction (parallel to stagnation line) (m/s)
w'	rms of fluctuating velocity component in spanwise Z direction (m/s)
x	distance downstream of the grid (m)
λ_x	streamwise integral length scale of turbulence (m)
ω_y	rms of fluctuating vorticity component in spanwise Y direction (1/s)
ω_z	rms of fluctuating vorticity component in spanwise Z direction (1/s)

An alternative to developing a correlation using standard regression analysis is to train a neural network (NN) to predict the stagnation region heat transfer. The advantage of this is that the trained neural network can then be used to perform a sensitivity analysis of the turbulence parameters on stagnation region heat transfer. This is particularly useful as it allows some insight into the physics of the problem, especially when the underlying physical–mathematical model is complicated. Neural networks have been used successfully in many engineering applications and are capable of representing the physical knowledge of complex systems. A neural network extracts knowledge from the data presented to it, where the physical knowledge of the system is contained within the rules of the network.

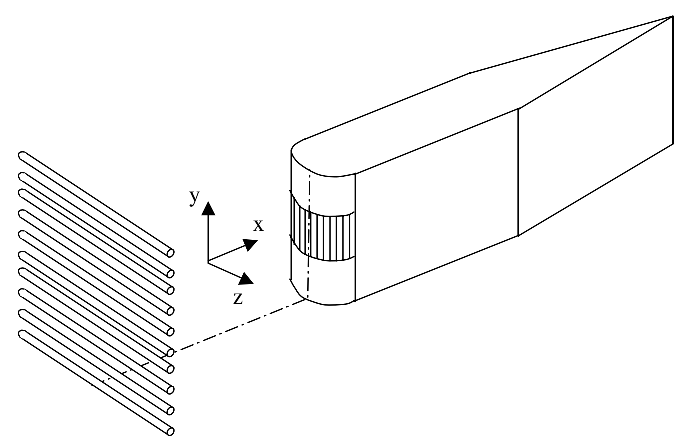
The objective of this paper is to present a neural network technique to predict stagnation region heat transfer in the presence of freestream turbulence. The neural network was trained using experimental data, and Re_D, λ_x, u', v', w', ω_y and ω_z were used to characterize the freestream turbulence. The trained neural network was then used to perform a sensitivity analysis of the freestream turbulence parameters on the stagnation region heat transfer.

2. Experimental facilities

The experimental data used to train the neural network were obtained using a heat transfer model with a cylindrical leading edge in a low-speed wind tunnel. The test section of the wind tunnel is 1-m × 1-m and 20-m in length, with freestream turbulence levels with no turbulence generating grids less than 0.5% at all flow rates. Freestream turbulence with different characteristics was generated using grids of 2.86 cm, 1.59 cm and 0.95 cm diameter parallel rods. The grids were arranged in two different orientations, perpendicular and parallel to the stagnation line (Fig. 1), to obtain freestream turbulence with different and distinct characteristics. For example, for the perpendicular grid orientation, the vortices in the freestream turbulence would be primarily aligned perpendicular to the stagnation line and be more susceptible to stretching as they pass over the stagnation region. All three components of the fluctuating velocities, integral length scale and the spanwise fluctuating vorticity components, ω_z and ω_y, were measured using single and X-wires and a vorticity probe. Heat transfer measurements were made with the grids $25d$ to $125d$ upstream of the model at three different Re_D of 67,750, 108,350 and 142,250. The heat transfer model has a cylindrical leading edge of diameter 20.32-cm. A constant heat flux surface is maintained by electrically heating nineteen strips of 0.005-cm-thick stainless steel foil that are evenly



(a) Grids in parallel orientation



(b) Grids in vertical orientation

Fig. 1. Arrangements of turbulence generating grids.

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