

Experimental And Numerical Study Of Air Jet Impingement On Heated Cylinder

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1. Introduction

Jet impingement is a widely used technique to achieve higher heat transfer from a surface both for cooling and heating purposes. It offers advantages namely simplicity in construction and higher heat transfer rates. Further, the technique is cost-effective and can provide better heat removal than uniform flow. The technique is employed in numerous engineering applications including glass manufacturing, paper drying, gas turbine blades, electronic components and food processing. Further, it is utilized in multiple processes namely drying, heating as well as cooling of surfaces.

2. State of Art including Research Gaps

The jet impingement cooling technique has been extensively studied over the past 50 years. The literature for flat plate is extensive [1-5]. These cover various aspects including nozzle geometry, entrainment boundary, spacing between jet and impinging surface, surface curvature, number of nozzles, Reynolds number etc. However only a few researchers have investigated jet impingement on curved surfaces namely cylinder, convex or semi-cylindrical surfaces.

The published research [Tawfek, Esirgemez, Singh, Singh, Dewan 2012] on circular impinging jets on cylinders indicates a research gap in numerical studies involving an equation turbulence model. The existing research primarily focused on experiments and two-equation turbulence models $k-\epsilon$ (standard, RNG and realizable) and $k-\omega$ (standard, SST). Therefore, we conducted a numerical investigation using the original and modified versions of the $v2f$ turbulence model. Moreover, we have compared the turbulence models based on their accuracy in prediction.

The previous literature [Brahma, Gori, Gori, Nada, Gau] on slot jets reveals a scarcity of literature focusing on the investigation at the rear of the cylinder. Such a study aims to address potential heat transfer intensification. Therefore we have put a semi-circular confinement having a bottom opening at cylinder's rear. The analysis includes an examination of heat transfer behaviour for the relevant parameters. The investigation also involves determining optimal opening angle (α) for achieving maximum cooling from the cylinder.

The configuration of impinging a jet on a cylinder placed on a flat plate is a very common configuration concerned with applications of food engineering where the cylinder is treated as a food product. Although prior studies [Olsson, Nitin, Singh and Singh] are available, they focus primarily on

numerical study with uniform temperature as a thermal boundary. Therefore we have addressed the issue by conducting experiments. Additionally, we have introduced varying plate lengths as an additional parameter to conventional parameters. Moreover, we have established an appropriate heat transfer correlation for the configuration.

Hence in summary, we have addressed following problems during the Ph.D. work, □ Numerical investigation of circular impinging jet on cylinder using RANS approach.

Numerical study for slot impinging jet on the cylinder with semi-circular confinement using RANS turbulence modelling.

Experimental study of impinging jet configuration for applications in food engineering.

3. Objectives

The primary objective is to perform the experiments and numerical analysis of air impingement cooling from the heated cylinder. This includes configurations involving a semicircular confinement, a flat plate and the absence of these surfaces. The specific objectives are as per below,

To examine heat transfer behaviour for heat transfer intensification in the presence of semicircular confinement.

To determine the optimal angle of opening for maximizing heat transfer for relevant parameters.

To compare k - ϵ and k - ω based turbulence models with four equation ($v2f$) turbulence models based on thermofluid behaviour.

To identify the most effective turbulence model for precise numerical prediction.

To assess the thermal behaviour of configuration concerned with food engineering applications. □ To establish heat transfer correlations for relevant configuration.

4. Methodology for Investigation

4.1. Experimental Investigation

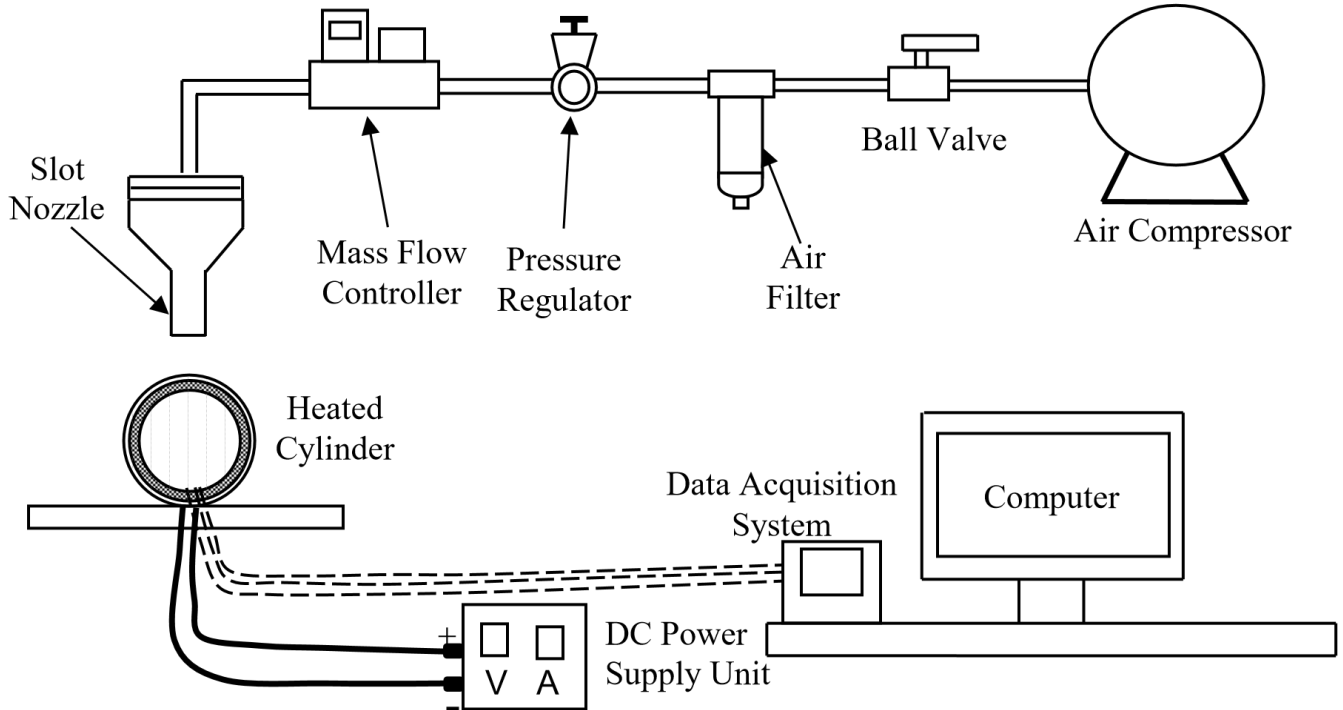


Fig.1 Experimental Test Set-up used for Ph.D. work

We have established the experimental facility at the National Institute of Technology – Manipur as illustrated in Fig. 1. The Financial support was provided through the Early Career Research (ECR) Award from the Science and Engineering Research Board (SERB).

The test facility includes the modules including an air supply unit, an electrical heat supply assembly and a data collection unit. The air supply unit consists of an air compressor, ball valve, air filter, pressure regulator, mass flow controller and jet. The heating of the cylinder is provided by DC electrical current using a DC power supply. The data collection unit includes a data acquisition system linked to a computer. The thermocouples inserted inside the cylinder are connected to the data collection unit where temperature history is monitored and recorded.

$q'' D$

$Nu_{\theta} = \frac{q'' D}{k (T_{\theta} - T_{jet})}$ Here Nu_{θ} = Nusselt number (local), q'' = wall heat flux, T_{θ} = cylinder temperature at the angular location, T_{jet} = jet temperature, D = cylinder diameter and k = thermal conductivity. We have inserted 8 thermocouples along the circumferential and 2 thermocouples in the axial direction of the cylinder.

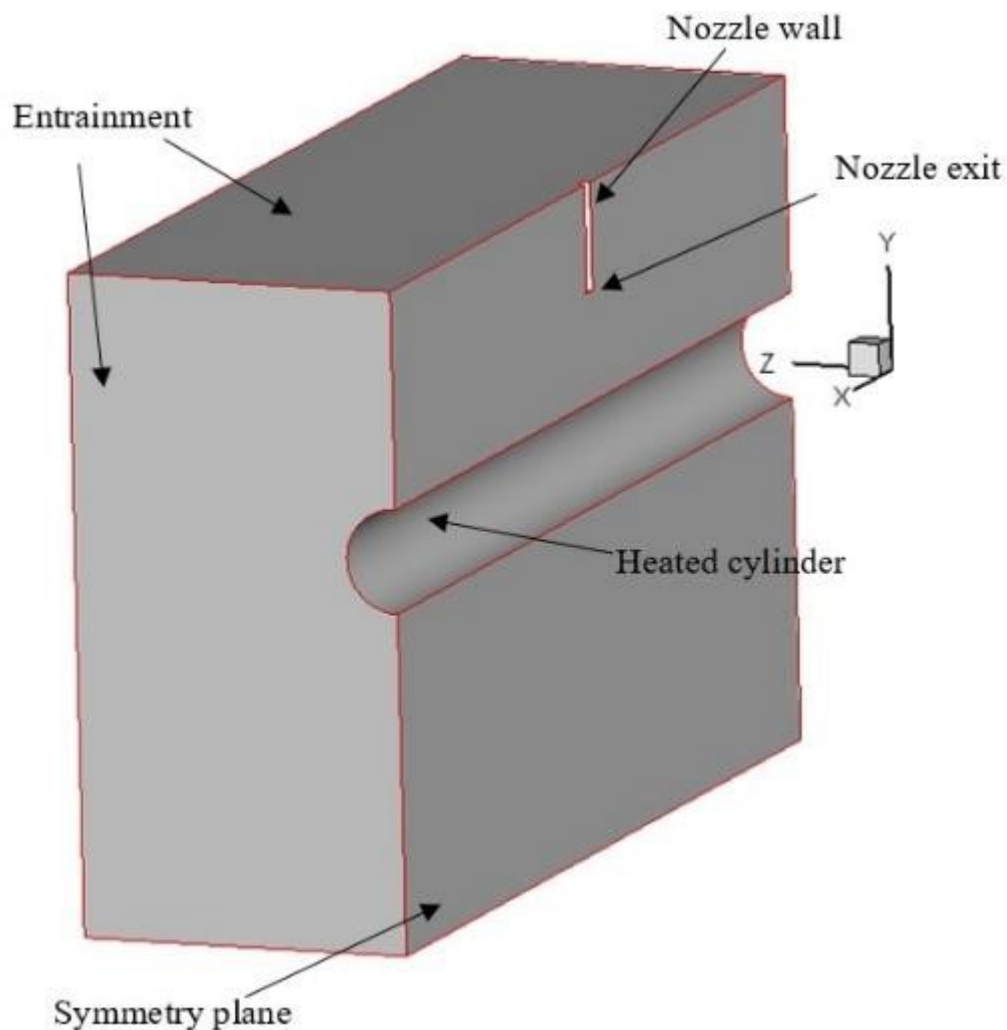
4.2. Numerical Analysis

We have conducted numerical study from finite volume based CFD (Computational Fluid Dynamics) modelling. The CFD solvers OpenFOAM (Open Source CFD Package) and ANSYS – Fluent (Commercial CFD Package) were utilized.

The numerical study for complex phenomenon involving impinging jet is executed by solution of “Navier Stokes Equations of Motion (Conservation of Mass and Momentum)” and “Energy Equation (Conservation of Energy)”. RANS and LES serve as frameworks for solution of concerned equations. Their information are provided in PDF (Post-Doctoral Fellowship) Proposal. However as Ph.D. work is concerned, we have utilized RANS only.

5. Key Findings

5.1. Round Jet Impingement (Numerical Study)



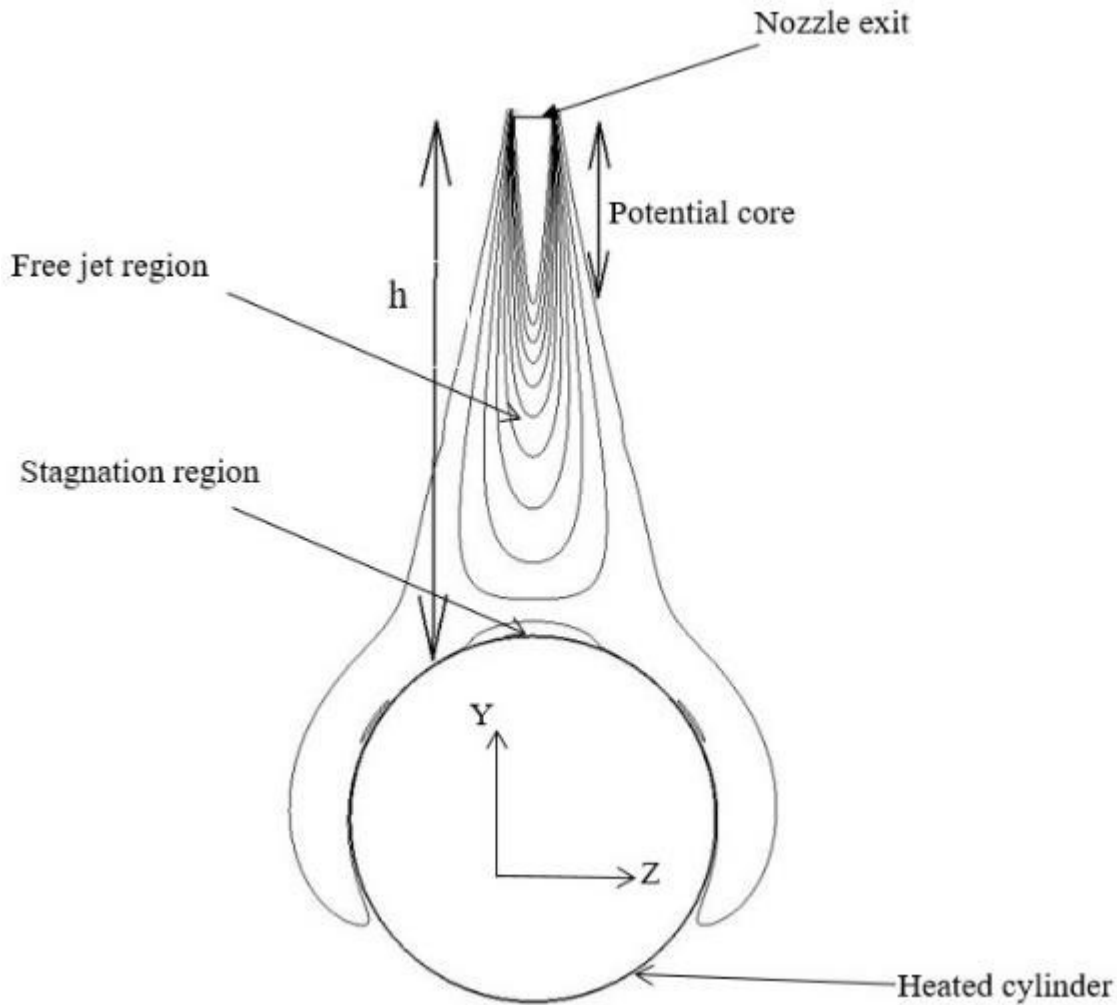


Fig.2 (a) 3D Computational Domain (b) Flow Regimes

[ASME - Journal of Heat Transfer]

The impinging surface (cylinder) has a uniform temperature of 308 K whereas the jet temperature is 300 K. The cylinder diameter (D) and length are 50 mm and 500 mm whereas jet diameter (d) is 7 mm. The jet-cylinder spacing (h/d) varies from 7.5 - 15. The jet Reynolds number ($Re_d = \rho U d / \mu$) is 23,000 - 38,800. The computational domain is as per Fig.2 (a) whereas flow regimes are as per Fig.2 (b).

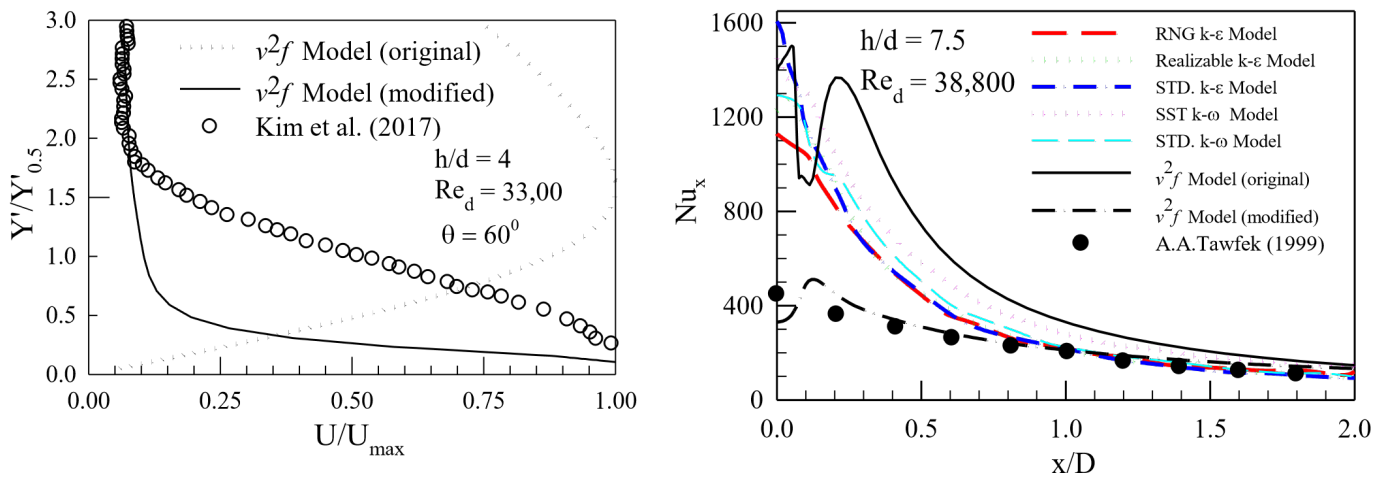


Fig.3 (a) Fluid Flow – Mean Streamwise Velocity (b) Heat Transfer – Axial Nusselt number

[ASME – Journal of Heat Transfer]

As shown in Fig. 3(a), the modified v^2f model follows the experimental mean-velocity distribution more closely than the original v^2f model, which shows a substantially different trend.

Among various $k - \epsilon$ and $k - \omega$ turbulence models; RNG $k - \epsilon$ shows less error for Nu prediction than other models at $x/D = 0$ (stagnation point). Furthermore, the modified v^2f model's prediction of Nu at $x/D = 0$ quite aligns with the experimental. Additionally, in the wall jet region from $x/D = 0.8$ to 2; the original v^2f model and other $k - \epsilon$, $k - \omega$ based models predict results than experimental. However modified v^2f model's prediction closely matches with the experimental as shown in Fig.3 (b).

The original v^2f model has model constants depending on wall distance whereas modified v^2f model possesses model constants independent of it. Moreover, Davidson et al. [21] introduced limits for the v^2 source term and turbulent viscosity. These modifications in turbulence model results in excellent numerical predictions comparable to experiments.

5.2. Impingement of Slot Jet with Semi-circular Confinement (Numerical Study)

The semi-circular confinement modifies the flow pattern and influences heat transfer. Therefore it is put at the rear of the cylinder to improve heat transfer there.

$$Re_D = \rho U D / \mu$$

Fig.4 (a) shows a configuration where confinement is put at the cylinder's rear portion for heat transfer investigation. The cylinder's diameter (D) is 36 mm whereas slot breadth (S) is 3.6 mm and the confinement radius is 22.5 mm. The jet-to-cylinder spacing (h/S) is 4, 6, 8 and 10; the Reynolds

number (Re_D) is 30,000 – 90,000 whereas the confinement angle (α) is 0° – 120° .

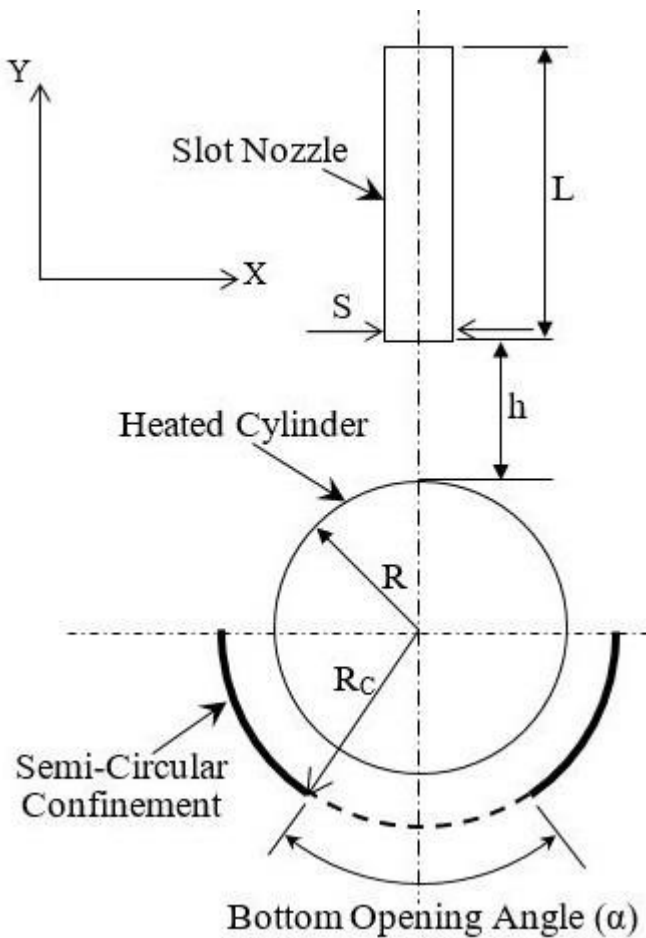


Fig.4 (a) Jet Impingement Configuration (b) Variation of Mean Nusselt number w.r.t. (α)

[International Journal of Thermal Sciences]

Table - 1 The % increment in Num for $\alpha = 60^\circ$ and $\alpha = 70^\circ$ (relative to closed confinement)

[International Journal of Thermal Sciences]

$\alpha = 70^\circ$ $\alpha = 60^\circ$

h/S Reynolds Number (Re_D)

30,000 50,000 70,000 90,000 30,000 50,000 70,000 90,000

4 37.13 46.73 48.59 53.60 57.09 60.20

6 45.49 46.89 49.43 51.63 36.69 40.08 44.76 48.17

8 35.11 41.33 42.66 45.31 35.11 41.78 43.13 45.67

locations they are opposing.

5.3. Cylinder Placed on Flat Plate (Experimental Study)

The cylinder with uniform heat flux boundary imposed by electrical heating is symmetrically positioned on the flat plate as per Fig.5. The cylinder's diameter (D) is 50 mm whereas plate lengths (P) equal to $D/2$, D and $2D$ which are 25 mm, 50 mm and 100 mm. The rectangular jet has slot breadth of 3.6, 4.5 and 5.4 mm. The jet-cylinder spacing (h/S) is 4, 8, 12 whereas Reynolds number (Re_D) varies as 10,000; 15,000; 20,000; 25,000. We have employed the experimental investigation for a full factorial investigation of these parameters.

The Nu_S increases with increasing S/D , increasing Re , decreasing h/S whereas P/D does not affect it. The Nusselt number (local) gets modified between $\theta = 0^\circ - 60^\circ$ with changing h/S whereas it gets affected between $\theta = 0^\circ - 180^\circ$ with changing Re_D and S/D . Local Nusselt number particularly in region from $\theta = 120^\circ - 180^\circ$ gets improved with increasing P/D . The correlations for Nu_S and Nu_m were developed from "Regression Analysis" with $R^2 = 0.98$ and $R^2 = 0.91$.

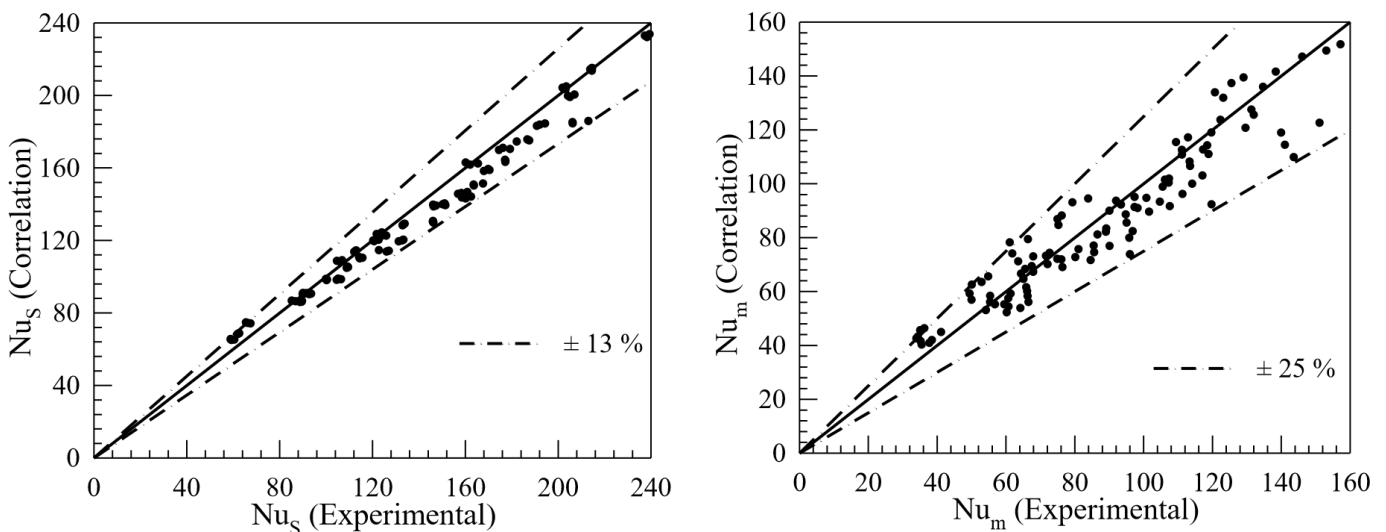


Fig.6 Parity Plots for (a) Nu_S (b) Nu_m

[ASME – Journal of Thermal Science and Engineering Applications] The correlations are,

$$h = -0.12 + 1.26 P - 0.005$$

$$Nu_S = 4.19 Re_D^{0.69} (S) (D)$$

(3)

$$h = -0.1 S + 1.17 P - 0.022$$

$$Nu_m = 0.86 Re_D^{0.78} (S) (D)$$

(4)

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Nomenclature

(k – turbulence kinetic energy, ε – dissipation rate, ω – specific dissipation rate, v_2 – normal velocity, f – relaxation frequency)

D

h d

ReD

Red

S

ACRONYMOS

RANS – Reynolds Averaged Navier Stokes

LES – Large Eddy Simulation

CFD – Computational Fluid Dynamics