ABSTRACT

The use of impinging fluid jets for rapid cooling or heating application is a well-established technique, particularly effective for localized cooling of heated surfaces in space-constrained scenarios. Traditionally, jet impingement has been widely employed in industries such as metal processing and casting, gas turbine blade cooling, rocket launcher systems, rotary cement kiln shell cooling, and welding spot cooling for large-diameter offshore pipelines. Its versatility stems from the flexibility to adjust various flow and geometric parameters, making it adaptable to diverse operational requirements.

Despite the wealth of research on jet impingement heat transfer, a critical gap remains in understanding its application to spherical convex and concave surfaces. In recent years, impingement cooling has found relevance in high-power laser systems, high-performance microprocessors, electrified automobiles, etc. These are new and emerging engineering applications where spherical surfaces may be encountered. For instance, directed energy weapon systems rely on high-intensity laser beams guided by convex and concave spherical lenses or mirrors, which require efficient cooling to minimize thermal distortions. In such scenarios, impingement cooling via cold air jets offers a promising and effective solution.

This study presents a combined experimental and numerical investigation of turbulent flow and heat transfer characteristics during circular air jet impingement on convex and concave spherical surfaces subjected to a constant heat flux. The specific research objectives are as follows:

- Experimental investigation of the heat transfer characteristics of a round air jet impinging on a hemispherical convex surface. Development of correlations from the experimental data to predict the stagnation point and average Nusselt numbers for the hemispherical convex surface.
- Numerical analysis of the jet impingement on a hemispherical convex surface using the v^2-f turbulence model across a broad range of dimensionless parameters. Assess the effects of key dimensionless parameters on; potential core length of the jet, stagnation point Nusselt number, and local Nusselt number distribution over the convex surface.
- Derivation of correlations from extensive numerical data to estimate local Nusselt numbers at various positions on the convex surface.

- Numerical investigation of jet impingement on bowl-shaped concave spherical surfaces using the *v2-f* turbulence model. Analyse the impact of dimensionless parameters on; potential core length, stagnation point Nusselt number and local Nusselt number distribution over the concave surface.
- Analysis of the influence of concave curvature on thermal behaviour by systematically comparing Nusselt number data between concave and flat surfaces under identical flow and geometric conditions. Development of correlations from the extensive numerical data to predict the stagnation point Nusselt numbers on the concave bowl-shaped surfaces.

Detailed experimental studies were conducted to analyze the heat transfer characteristics of circular air jet impingement cooling of convex hemispherical surfaces. Empirical correlations were developed from the experimental data to predict both stagnation point (Nu_0) and average Nusselt numbers (Nu_{avg}) across a broad range of dimensionless parameters. The relevant dimensionless parameters are, nozzle-to-surface distance (L/d), diameter ratio of surface and nozzle or relative curvature (D/d), jet Reynolds number based on nozzle diameter (Re_d) and curvilinear distance along the surface (r/d). Also, corresponding numerical simulations employing the v^2-f turbulence model were also performed. The key findings are given below:

- *Stagnation point and average Nusselt numbers:* Both Nu_0 and Nu_{avg} are a strong function of Re_d across all ranges of parameters. Nu_0 remains relatively unaffected by dimensionless nozzle-to-surface distances for $L/d \leq 6$ but follows power-law decay for $6.67 \leq L/d \leq 16.67$.
- *Influence of Relative Curvature*: The D/d values significantly affects both Nu_0 and Nu_{avg} across all tested nozzle-to-surface distances ($2 \leq L/d \leq 16.67$) and jet Reynolds numbers ($29{,}000 \leq Re_d \leq 80{,}000$).
- *Local Nusselt number distribution:* In case of $L/d = 2$, a distinct secondary peak in the local Nusselt number profile is observed at $r/d \approx 2$.
- The v^2-f turbulence model is quite good at simulating the jet impingement phenomena. The simulation results give a local Nusselt number distribution around the target surface with a maximum *20%* deviation from the experimental data.

An exhaustive computational analysis employing the v^2-f turbulence model was carried out to evaluate the thermo-fluidic characteristics of circular air jet impinging on convex hemispherical surfaces. The study systematically examined the influence of relevant non-dimensional parameters on Nusselt number and flow dynamics. The key findings are briefly enumerated below:

- *Potential core length*: Based on the jet centerline velocity decay to 95%, the potential core length of the circular jet decreases with increasing Reynolds number (Re_d), ranging from *3.5d* at $Re_d = 11{,}000$ to *2.6d* at $Re_d = 50{,}000$. However, when defined as centerline velocity decay to 90%, the potential core length remains nearly constant at *5d* across the entire range of parameters.
- *Stagnation point Nusselt number (Nu_0)*: It is maximum at $L/d = 8$ for all the relative curvature (*D/d*) and Re_d values. For, $L/d \leq 4$ and $Re_d \geq 23000$, a secondary maxima is observed in the local *Nu* distribution. The Nu/Nu_0 values at local minima and maxima decrease with decreasing values of *D/d* for the same *L/d* and Re_d. This ratio (Nu/Nu_0) also decreases with decreasing Re_d at the same relative curvature.
- *Spatial Nusselt number distribution*: For, $0 \leq r/d \leq 1.3$ (when $L/d \leq 4$ and $Re \geq$ 23,000), *Nu* decreases linearly along the surface, strongly influenced by *D/d*. After the secondary peak, the local Nusselt number falls exponentially with respect to *r/d* as, $Nu \propto exp\{-0.2(r/d)\}$. In this region, *L/d* has minimal effect, while *D/d* remains influential.

A comprehensive numerical investigation employing the v^2-*f* turbulence model was conducted to examine the thermo-fluidic behaviour of the impingement cooling of concave bowl-shaped spherical surface using round air jets. For comparative analysis, computations were also performed for a flat surface under identical conditions. The study reveals distinct flow dynamics for concave surfaces compared to convex and flat configurations. The major inferences drawn from the results of the numerical computations are enumerated below:

- *Potential core length:* At low Re_d, the potential core length shortens significantly for concave surfaces compared to free jets or convex surfaces. The potential core length is also almost independent of Re_d for a fixed relative curvature (*D/d*), and increases with the increasing *D/d* value.
- *Heat transfer characteristics:* Concave curvature induces two opposing effects: (i) Enhanced heat transfer due to improved fluid mixing and turbulence. (ii) Reduced heat transfer caused by recirculation of heated fluid within the bowl-shaped volume.

- *Stagnation point Nusselt number*: Nu_0 are lower for concave surfaces than flat ones but approach flat-surface values as *D/d* increases. Nu_0 peaks at *L/d* = 6 across all tested parameter ranges and exhibits strong Reynolds number dependence. For $2 \leq L/d \leq 6$, Nu_0 shows a weak positive correlation with *L/d*, while for $8 \leq L/d \leq 10$, it shows a strong negative correlation. Increasing relative depth (*H/D*) consistently reduces Nu_0.
- *Local Nusselt number distribution:* In the region $0 \leq r/d < 1$, local *Nu* values are lower for concave surfaces than flat ones. Unlike convex/flat surfaces, no secondary peak in *Nu* distribution is observed for concave surfaces. For $L/d \leq 4$, *Nu* distributions of concave and flat surfaces converge when $r/d > 2$. For $L/d \geq 6$, convergence begins at $r/d > 1$.

The thermo-fluidic characteristics of dual-jet impingement on a convex spherical surface were studied through numerical computations with special emphasis on the jet-jet interaction. Parameters were varied as (same for both jets): *L/d* (*2–10*), Re_d (*10000–50000*), and *D/d* (*5–15*). Key observations are:

- *Fountain flow*: Opposing wall jets create a secondary stagnation zone, localized near the mid-plane. Width depends on *D/d* and Re_d; outside this zone, flow resembles a single jet.
- *Effect of Re_d, D/d, and L/d on Fountain zone width*: Higher Re_d compresses the fountain zone (*40%* reduction at when Re_d increases from *10000* to *50000)*. Increasing the *D/d* expands the fountain zone (in terms of *r/d*) and scaling is linear. *L/d* has minimal influence on the fountain width.
- *Heat transfer characteristics*: Peak *Nu* in fountain zone is 50–100% higher than the periphery, most enhancements is at low Re_d and small *L/d*. Sharp *Nu* drop downstream indicates rapid boundary layer growth.

The findings of the present study will be useful in the optimum design of the jet impingement cooling of the convex and concave spherical target surfaces.