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Experimental study of curvature effects on jet impingement heat transfer on concave surfaces

Zhou Ying [a], **Lin Guiping** [a], **Bu Xueqin** [a,*], **Bai Lizhan** [a,b], **Wen Dongsheng** [a,b]

[a] *School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China*
[b] *School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK*

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Abstract Experimental study of the local and average heat transfer characteristics of a single round jet impinging on the concave surfaces was conducted in this work to gain in-depth knowledge of the curvature effects. The experiments were conducted by employing a piccolo tube with one single jet hole over a wide range of parameters: jet Reynolds number from 27,000 to 130,000, relative nozzle to surface distance from 3.3 to 30, and relative surface curvature from 0.005 to 0.030. Experimental results indicate that the surface curvature has opposite effects on heat transfer characteristics. On one hand, an increase of relative nozzle to surface distance (increasing jet diameter in fact) enhances the average heat transfer around the surface for the same curved surface. On the other hand, the average Nusselt number decreases as relative nozzle to surface distance increases for a fixed jet diameter. Finally, experimental data-based correlations of the average Nusselt number over the curved surface were obtained with consideration of surface curvature effect. This work contributes to a better understanding of the curvature effects on heat transfer of a round jet impingement on concave surfaces, which is of high importance to the design of the aircraft anti-icing system.

1. Introduction

Heat transfer associated with jet impingement on a flat or curved surface has been the subject of extensive investigation for decades because of its enhanced local heat exchange performance in a wide variety of applications such as glass tempering, metal annealing, and engine and turbine blades cooling.[1,2] Impinging jets are also used in the hot-air anti-icing system of commercial aircraft where high-pressure hot air, bleeding from the engine, is ducted forward to a pipe with several small holes on it and impinges on the inner surface of the anti-icing cavity to heat the leading edge of wing. Since the anti-icing cavity is a curved surface, the effect of surface curvature should be taken into account when the jet impingement heat transfer performance is considered.

* Corresponding author.
E-mail address: buxueqin@buaa.edu.cn (X. Bu).

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Many experiments were designed to study the heat transfer of impingement jets, with a focus on flat plates. The very early experimental work for the flat plate case were represented by Gardon[3], Goldstein[4], Hrycak[5] and Beltaos et al.[6] with varying impingement distance, Reynolds number and oblique angle. Many measurement techniques based on naphthalene sublimation technique[7], temperature-sensitive liquid crystal[8,9] and thermal infrared camera[10,11] were adopted to measure and analyze the flow and heat transfer characteristics.

Metzger et al.[12] were probably the first to experimentally investigate the heat transfer characteristics of jets impinging on a concave cylindrical surface. The average heat transfer coefficient of single lines of circular jets was obtained with varied ratios of nozzle to surface distance H and nozzle diameter d at the Reynolds range from 1150 to 5500. Results indicated that the maximum heat transfer could be obtained at the optimum relative nozzle to surface $H/d = 3–5$, whose value decreased with increasing Reynolds number. Compared with the heat transfer performance on a flat plate, the stagnation point Nusselt number was higher on the concave cylindrical surface as reported by Hrycak.[13] Mayle et al.[14] also presented that the heat transferred to the boundary layer on the concave plate was greater than that on a flat plate.

Flow visualization facilities with smoke generation wire were applied by Gau and Chung[15] and Cornaro et al.[16] to visualize the flow structure of slot and round jet impinging on concave surfaces. The former result showed that the Nusselt number increased with increasing surface curvature for slot jet impingement on a concave surface, which was caused by the initiation of Taylor-Görtler vortices along the surface. Similar observation was also obtained by Cornaro et al.[16], who also found that the heat transfer rate on and around the stagnation point increased with increasing surface curvature. Lee et al.[17] experimentally investigated the local heat transfer from a long round jet impinging on a smaller relative curvature surface ($d/D = 0.034, 0.056, 0.089$) with jet Reynolds number from 11,000 to 50,000. Similarly Yang et al.[18] investigated the concave effect but using a slot jet in the range $5920 \leq Re_j \leq 25{,}500$, with a fixed slot-width to diameter ratio of 0.033. Their conclusions were consistent and indicated that the surface curvature and generation of Taylor-Görtler vortices were able to thin the boundary layer and enhance the heat transfer rates further in the downstream region apart from the stagnation point.

Since last decade, impinging jets have been applied to hot-air anti-icing system of aircraft and much progress has been achieved. Brown et al.[19] experimentally investigated the heat transfer in an aircraft nacelle anti-icing system and a correlation of average Nusselt number on the impingement area was presented with consideration of the distance between the jet holes and the jet Reynolds number. Papadakis et al.[20,21] conducted experiments in the NASA Glenn Icing Research Tunnel for a range of external conditions representative of inflight icing. The effects of hot air mass flow and temperature, angle of attack, tunnel airspeed and piccolo jet circumferential placement were investigated. Imbriale et al.[22] used IR thermography to measure 3D surface heat transfer coefficients by a row of jets impinging on a concave surface, representing an airfoil leading edge, and the influences of jet inclination, jet pitch and Reynolds number were analyzed. A more recent study by Bu et al.[23] investigated the heat transfer characteristics of jet impingement on a variable-curvature concave surface of a wing's leading edge experimentally. Parameters including jet Reynolds number, relative nozzle-to-surface distance and jet circumferential placement were considered for the effects on local Nusselt number distributions.

All of above researches indicated an enhanced heat transfer performance of jet impingement on concave surfaces. However the confinement effect of concave surface, which could decrease the heat transfer effect, was seldom studied. When studying 3D temperature distribution of a concave semi-cylindrical surface impinged by round jets, Fenot[24] noticed that the confinement effect actually reduced heat transfer as the average Nusselt number for the flat plate was higher than that for the curved plate. It was believed that the confinement prevented ambient air from mixing with the jet air, and thereby increased the flow temperature. The range of Reynolds number was from 10,000 to 23,000, and the relative surface curvature $d/D = 0.10, 0.15, 0.20$ and $H/d = 2–5$.

Öztekin et al.[25] investigated the heat transfer characteristics of slot jet impingement on concave surface for jet Reynolds number from 3423 to 9485 and the dimensionless surface curvature $R/L = 0.50, 0.75$ and 1.30, where R was the surface radius and L the surface trace length. Results indicated that, compared with the flat plate, the average Nusselt number along the concave surface was larger when $R/L = 0.75$ and 1.30. The average Nusselt number increased with increasing dimensionless surface curvature R/L, in other words, with decreasing relative surface curvature d/D. A slight increase in Nusslet number with decreasing d/D was also observed in Martin and wright's experiment[26] with single row of round jets impingement on a cylindrical surface. This trend was more prevalent for larger nozzle to surface distances in the range of jet Reynolds number from 5000 to 20,000, relative nozzle to nozzle spacing from 2 to 8, nozzle to surface distance from 2 to 8, and $d/D = 0.18, 0.28$.

As briefly reviewed above, although different studies have shown that surface curvature enhanced the heat transfer, detailed mechanism of heat transfer decay on a concave surface is still not well understood. This work conducted an extensive experimental study focusing on the curvature effect along the curved surface. By analyzing the stagnation point Nusselt number, and the average and local Nusselt number distributions in chordwise and spanwise directions, both the enhancement and confinement effects of the surface curvature were investigated. In addition, experimental data-based correlations of the average Nusselt number over the curved surface with consideration of the surface curvature effect were presented and experimentally verified.

2. Experimental apparatus

Fig. 1 schematically shows the jet impinging system used in this investigation. The main elements of the experimental apparatus were a steel pipe with a round nozzle on it and an impingement surface. Both were mounted on independent brackets to keep the surface horizontal and the pipe vertically removable for different nozzle to surface distances. As indicated in Fig. 1, the high pressure air from the air compressor became much cleaner and more stable after passing through the filter and air tank, and then went through the electronic pressure regulator where its pressure was adjusted to the desired value. The adjusted air flowed into the pipe from one