MACH NUMBER EFFECT ON JET IMPINGEMENT HEAT TRANSFER

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Impinging jets of air technique is a commonly used method to cool advanced aircraft turbines as it produces relatively large forced-convection heat transfer coefficients. Numerous experimental studies have been conducted to evaluate the flow and heat transfer characteristics associated with jet impingement on surfaces. All these studies bring in large injection diameters compared to those effectively used in turbojet engine turbine blades in order to obtain good accuracy in the measurements. The Reynolds number similarity is then introduced to link the experiments to the real injection conditions of the turbojet engine. Keeping the Reynolds number constant and increasing the jet diameter lead to an important reduction of the injection Mach number in the experimental apparatus. As the Mach number can reach nowadays values as high as 0.4–0.5 in modern turbojet turbines, we have undertaken an experimental study in collaboration with S.N.E.C.M.A. (Société Nationale d'Etude et de Construction de Moteurs d'Avion) to evaluate the Mach number influence on the impingement heat transfer coefficient.

EXPERIMENTAL TECHNIQUE AND APPARATUS

Our study is concerned with a circular free air jet impinging on a flat plate. The method is based on the use of three injection tubes with different interior diameters (D): 5mm, 10mm and 15mm. It enables the evaluation of three Nusselt number distributions over the impingement plate with three identical Reynolds numbers but with three different Mach numbers. Comparisons including the Mach number influence are then directly possible. Each injection tube is tested over the same Reynolds number range: from Re=7500 to Re=71000 which induces Mach numbers from 0.02 to 0.6 depending on the jet diameter. Three different jet-to-plate spacings are tested: H/D=2–5 and 10.

The injected flow is supplied by the building compressor. It is heated through the medium of an electric heater before going through a venturi. The jet flow is heated so that the jet total temperature is equal to ambient temperature. The venturi gives the mass flow rate with the aid of a differential pressure converter. It was designed to work in the incompressible range for all the considered tests and its discharge coefficient was measured over a wide range of mass flow rates. Flowmeters are used in conjunction with the venturi for very low flow rates for which the venturi is not perfectly adapted. Several Type-K-thermocouples measure the flow temperature along the air duct. A thermocouple for which the recovery factor was calibrated provides the jet center temperature at the jet exit. It is removed just before each test run not to interfere with the flow when temperature measurements are made on the test plate.

Injection tubes are pipes long enough (30D) to obtain a fully developed flow at the jet exit. Each injection tube has its own impingement test plate. The test plates are circular and their diameter is proportional to the jet diameter (20D). They are made of epoxy resin (e=1.6 mm thick, k_w=0.32 ±2.5% W/mK). An electric copper circuit (17.5 μm thick) is printed on each plate. It is located on the impingement side of the plate. It heats the plate by Joule effect. Its local resistivity has been calculated and experimentally checked. A correction is introduced to take the variation of resistivity with temperature into account during the test runs. The circuit is designed to provide a non-uniform axisymmetric heat flux density so that the plate surface temperature is nearly uniform (around 60°C) when it is cooled by the impinging air jet (Fig. 1). Thus radial heat conduction can be neglected. Furthermore the difference of temperature between the air and the plate surface can be kept as high as possible all over the plate (including the impingement region) without damaging the plate. It guarantees a very good accuracy on the entire surface in the local heat transfer coefficient calculation. The surface temperature distribution on the plate side opposite the impingement (back side) is measured using an infrared camera. A monodimensional conduction calculation is then used to give the temperature field of the impingement side (front side). This allows a complete mapping of the heat transfer coefficient over the entire impingement plate. Both sides of the plate are painted in black to give the surfaces the high and uniform emissivity required by infrared camera measurements. This emissivity was calibrated (ε=0.96±0.02).

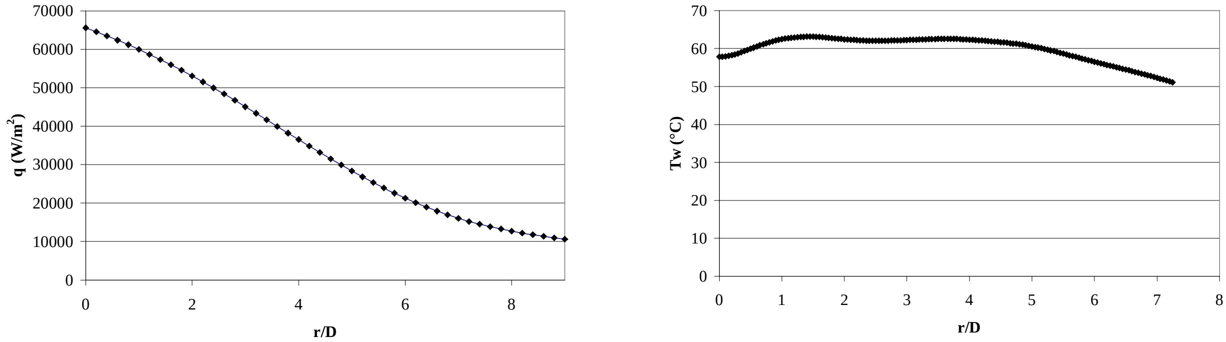

Fig. 1: Example of heat flux density q and wall temperature distribution T_w over the impinged plate.

Each test run is done in two parts. The first experiment provides the wall adiabatic temperature T_{aw} distribution by measuring the temperature distribution on the test plate when the wall heat flux is zero. The adiabatic wall temperature will be used as the reference temperature in the heat transfer coefficient calculation. The second experiment yields the wall temperature field T_{mes} on the plate back side when the plate is heated with the heat flux density distribution q(r). The wall temperature on the plate front side is then referred to as T_w and the ambient temperature as T_{amb}. The impingement side heat transfer coefficient h and corresponding Nusselt number Nu based on the jet diameter D are calculated taking into account corrections for radiation losses on the plate front side and radiation and convection losses on the plate back side (overall coefficient h_r).

$$h = \frac{q - \varepsilon\sigma\left(T_w^4 - T_{amb}^4\right) - h_r\left(T_{mes} - T_{amb}\right)}{T_w - T_{aw}} \qquad T_w = T_{mes} + \frac{e}{k_w} h_r\left(T_{mes} - T_{amb}\right) \qquad Nu = \frac{hD}{k_{air}}$$

RESULTS

The local Nusselt number distribution have been obtained for each injection configuration (Fig. 2). The radial distribution of Nu has been averaged to give the mean Nusselt number:

$$\overline{Nu}(R) = \frac{2}{R^2}\int_0^R Nu(r)rdr$$

The results are consistent with those of Baughn & Shimizu[1] and Hollworth & Gero[2]. Local Nusselt number of Goldstein et al.[3] are slightly lower than the ones measured in the present study. The discrepancies can certainly be attributed to the differences in the experimental techniques and in the injection conditions as Goldstein et al. used an ASME nozzle whereas a long pipe with a fully turbulent flow is used here.

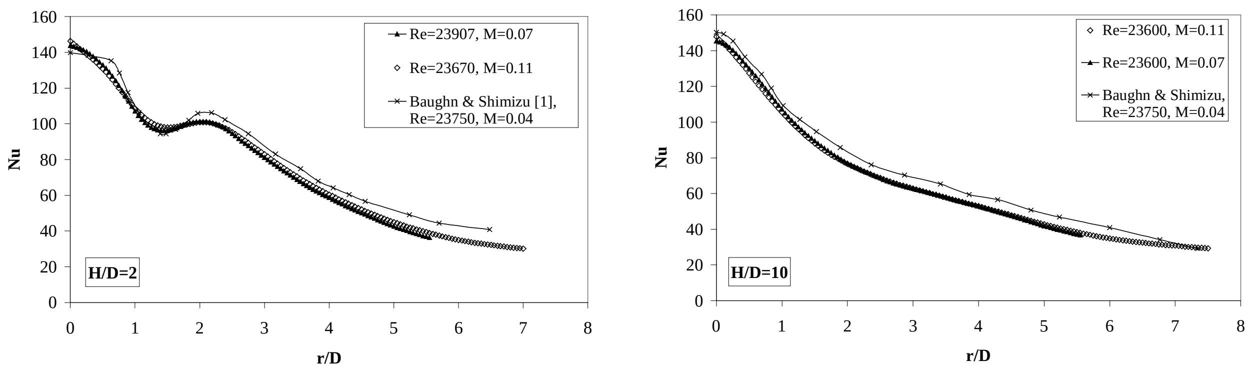

Fig 2: Examples of Local Nusselt number distribution along the impingement surface.

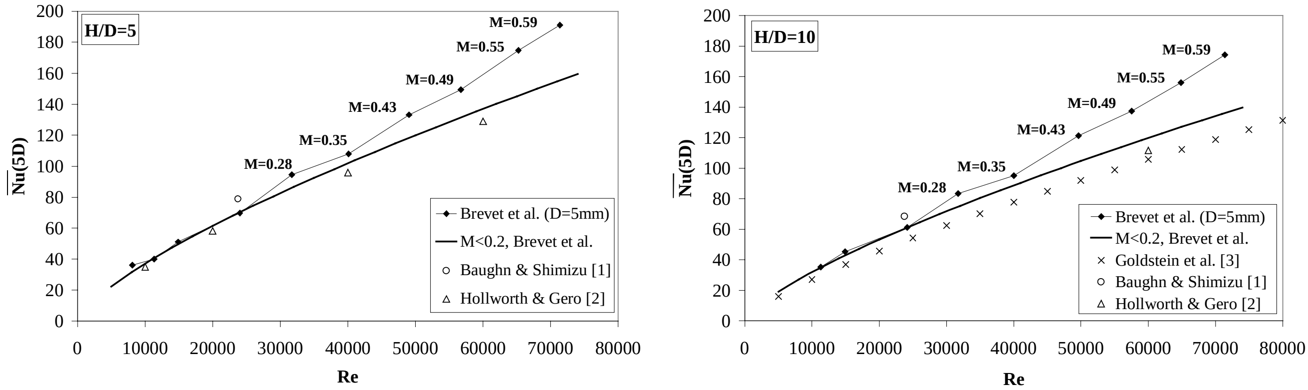

Fig 3: Variation of mean Nusselt number (R=5D) with Reynolds and Mach numbers.

At a given impingement distance H/D it appears that the mean Nusselt numbers fit the same function of Reynolds number Re independently of the jet diameter and independtly of the Mach number M as long as M doesn't exceed a value of 0.2. The dependence of $\overline{Nu}$(R=5D) can then be approximated by a power-law dependence based on $Re^{0.74}$, which is very close to the results of Goldstein et al[3] and Huang & El Genk[4] (who give $Nu \propto Re^{0.76}$). When M exceeds a value of 0.2, a divergence from the initial curve has been observed (Fig. 3): the mean Nusselt number is still mainly ruled by the Reynolds number but a high Mach number (>0.2) increases sensibly the mean Nusselt number. Thus the mach number influence on heat transfer should be taken into account for high velocity impinging jets. A correlation linking the mean Nusselt number calculated for R equal R/D, Re, M, and H/D has been computed and fit the data within ±15%.

REFERENCES

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