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A heat transfer measurement of jet impingement with high injection temperature

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Abstract

Local heat transfer from an impinging high temperature jet is studied using a method based on the heat thin foil technique and on the infrared thermography. Heat thin foil technique is used to impose several heat fluxes. For each flux, the temperature distribution is recorded using infrared imaging. Local heat transfer coefficients and adiabatic wall temperatures are determined by means of a linear regression method. This procedure is validated for a single round jet impinging on a flat plate for a range of injection temperatures. ***To cite this article: M. Fénot et al., C. R. Mecanique 333 (2005).***

Résumé

Mesure des transferts de chaleur dus à l'impact d'un jet à une température d'injection élevée. Les transferts de chaleur locaux, dus à l'impact d'un jet dont la température d'injection est élevée, sont déterminés en utilisant une méthode basée sur l'emploi simultané de la technique du film chauffant et de la thermographie infrarouge. Le film chauffant permet d'imposer plusieurs flux. Pour chacun d'eux, la distribution de température est enregistrée par mesure infrarouge. Les coefficients de transfert de chaleur locaux et les températures adiabatiques de paroi sont calculés par régression linéaire. Cette méthode est validée dans le cas d'un jet unique axisymétrique en impact sur une paroi plane pour plusieurs températures d'injection. ***Pour citer cet article : M. Fénot et al., C. R. Mecanique 333 (2005).***

Keywords: Fluid mechanics; Jet impingement; Heat transfer coefficient

Mots-clés : Mécanique des fluides ; Impact de jet ; Coefficient d'échange

Version française abrégée

Dans la majorité des procédés industriels utilisant l'impact, la température des jets diffère de celle de l'environnement, ce qui provoque un entraînement thermique de l'air ambiant dans le jet et modifie la température de celui-ci. Dés lors, la température d'injection, T_{j} prise comme température de référence, ne permet pas l'invariance des coef-

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ficients d'échange vis-à-vis de la température d'injection. Quelques auteurs [1–4] ayant étudié ces problèmes à trois températures (températures d'injection, ambiante et de paroi), ont conclu à l'invariance des distributions de coefficient d'échange h lorsque la température adiabatique de paroi T_{ad} est utilisée comme température de référence. Cependant, leurs essais de validation n'ont été effectués que pour des températures peu différentes de l'ambiante. Notre étude vise justement à l'analyse de l'impact de jets plus chauds (jusqu'à 140 °C). On utilise à cet effet une plaque d'impact fluxmétrique chauffée par effet Joule et qui permet donc une très bonne connaissance de la densité de flux électrique dissipée φ_{elec}. Les densités de flux perdues par rayonnement et par convection sur la face de la plaque ne subissant pas d'impact, sont déduites de φ_{elec} afin d'obtenir la densité de flux convecté entre le jet et la paroi d'impact φ_{conv} (Éq. (3)). La mesure de la distribution de température de la plaque d'impact est effectuée par l'intermédiaire d'une caméra infrarouge. Des densités de flux φ_{conv} croissantes sont imposées par l'intermédiaire du circuit électrique. Pour chacune de ces densités de flux, les températures de la plaque d'impact T_w sont mesurées. Pour chaque couple (φ_{conv}, T_w), l'Éq. (2) s'applique. On peut donc remonter à h et à T_{ad} par régression linéaire. Le coefficient d'échange h et la température adiabatique de paroi T_{ad} sont adimensionnés sous forme de nombre d'un Nusselt Nu et de l'efficacité η (Éqs. (5) et (6)). Cette méthode a été appliquée au cas d'un jet unique axisymétrique de diamètre $D = 10$ mm, impactant sur une paroi plane pour un nombre de Reynolds d'injection compris entre 8500 et 26 500, pour des distances d'impact adimensionnées H/D comprises entre 2 et 10 et pour des températures d'injection entre 20 °C et 140 °C. La Fig. 2 montre l'indépendance de la distribution du nombre de Nusselt par rapport à la température d'injection T_j, ce qui confirme l'hypothèse relative à l'utilisation de T_{ad} comme température de référence. L'efficacité η est maximale à l'impact et diminue avec la distance au point d'arrêt r/D au fur et à mesure que le jet se mélange avec l'air ambiant plus froid (Fig. 3). Pour les mêmes raisons, l'efficacité au point d'arrêt chute avec l'augmentation de la distance H/D. Pour finir les comparaisons des distributions d'efficacité pour les différentes températures d'injection démontrent une indépendance de ces distributions par rapport à T_j.

1. Introduction

Jet impingement is found in many industrial applications requiring high rates of heat transfer. These include the spot cooling of electronic components, the tempering of glass and the cooling of gas turbine blades. In many of these applications, jet injection temperature T_j differs from the ambient temperature T_{amb} and from the impinging surface temperature T_w. Under these conditions, the entrainment of ambient air into the jet changes its temperature and the heat flux exchanged by the impinging surface does not vary linearly with $(T_w - T_j)$ or with $(T_w - T_{amb})$. Other applications involving a non-monotonic variation of gas temperature across the boundary layer (film cooling or configurations with non-uniform wall temperatures like electronic cooling) are also concerned with this problem. However, few investigations have concerned jets with a higher temperature than the environment. Hollworth and Wilson [1] and Hollworth and Gero [2] have shown that local heat transfer coefficients are independent of $(T_j - T_{amb})$ if the adiabatic wall temperature T_{ad} is used as reference temperature T_{ref}. Goldstein et al. [3] have measured the effectiveness η (a dimensionless form of the adiabatic wall temperature) and have confirmed Hollworth and Gero's results for up to a temperature differences of 30 °C. Baughn et al. [4] have extended the Reynolds number range and jet characteristics of the result reported in [3]. In all these studies, the determination of T_{ad} is achieved by measuring the temperature of an isolated plate submitted to the impact of a jet. The principal problem of this method is that the plate should be isolated which is very difficult to obtain if the difference between jet and ambient temperatures is relatively high. The purpose of this Note is to present another method which may be used to determine jointly h and T_{ad} even for a large difference between T_j and T_{amb}.

2. Principle

The method for calculating h and T_{ad} is based on Newton's law of cooling:

$$h = \varphi_{conv}/(T_w - T_{ref}) \tag{1}$$

which can also be written:

$$T_w = \frac{\varphi_{conv}}{h} + T_{ref} \tag{2}$$

where φ_{conv} is the flux density exchanged between jet and plate and T_w the wall temperature. If φ_{conv} goes to zero, then, according to Eq. (1), $T_{ref} = T_w$. Thus, T_{ref} is equal to the wall temperature when there is no exchange between the plate and the flow, which is precisely the definition of T_{ad}. So $T_{ref} = T_{ad}$. Several tests are carried out with different couples (φ_{conv}, T_w). Since Eq. (2) is linear, it is possible to perform a linear regression, $1/h$ will be the slope and T_{ad} will be the Y-intercept. Moreover, the correlation coefficient of the linear regression r^2 is calculated to verify the alignment of data points (φ_{conv}, T_w). The number of couples used for the regression has been set to four; more couples will not improve the precision significantly.

3. Procedure and experimental apparatus

The demonstration of this experimental method relies on a single round air jet impinging on a flat plate for injection Reynolds numbers *Re* between 8500 and 26 500, an injection to plate spacing H between 2 and 10 injection diameters and a range of injection temperatures between T_{amb} ($\approx 20\,^{\circ}\mathrm{C}$) and $140\,^{\circ}\mathrm{C}$. The experimental apparatus is shown in Fig. 1. Jet flow is provided by a compressor. A valve and a venturi control and measure the mass flow rate. The air flow is brought to the desired temperature by an electric heater. The injection nozzle is a 300 mm long tube with an interior diameter of $D = 10$ mm. Tube is long enough to obtain a fully developed flow. A thermocouple measures the injection jet center temperature.

The jet impinges on a thick plate ($e = 1.6$ mm) made of Teflon (thermal conductivity $\lambda_w = 0.296 \pm 0.01\ \mathrm{W\,m^{-1}\,K^{-1}}$). Its upper side is covered with a thin copper foil (35 µm thick). An electrical circuit is engraved in this foil and heats the plate by Joule effect. The circuit resistivity has been measured and current intensity is recorded to determine the dissipated flux density φ_{elec}. The temperature of the back side of the plate T_{mes} (opposite of the impingement) is measured using an infrared camera (CEDIP Jade MWIR). The plate is painted in black (high emissivity: $\varepsilon_w = 0.95 \pm 0.02$) for a precise thermographic measurement. Taking into account radiative and convective losses the flux density exchanged between the jet and the plate φ_{conv} can be calculated from Eq. (3) and T_w can be deduced from T_{mes} with Eq. (4):

$$\varphi_{conv} = \varphi_{elec} - h_r(T_{mes} - T_{amb}) - \sigma\varepsilon_w\left(T_{mes}^4 - T_{amb}^4\right) - \sigma\varepsilon_w\left(T_w^4 - T_{amb}^4\right) \tag{3}$$

$$T_w = T_{mes} + \frac{e}{\lambda_w}\left[h_r(T_{mes} - T_{amb}) - \sigma\varepsilon_w\left(T_{mes}^4 - T_{amb}^4\right)\right] \tag{4}$$

where h_r is the heat transfer coefficient of the back side of the wall (measured by heating the plate without jet impingement).

For a given configuration ($Re, H/D, T_j, \ldots$), knowing φ_{conv} and T_w for each spatial position, it is possible to put into practice the method exposed in Section 2.

The heat transfer coefficient and wall adiabatic temperature calculated in this way are expressed in a dimensionless form: the Nusselt number *Nu* and effectiveness η, as shown in Eqs. (5) and (6) with λ_{air} is calculated at the T_{ad} temperature:

$$Nu = hD/\lambda_{air} \tag{5}$$

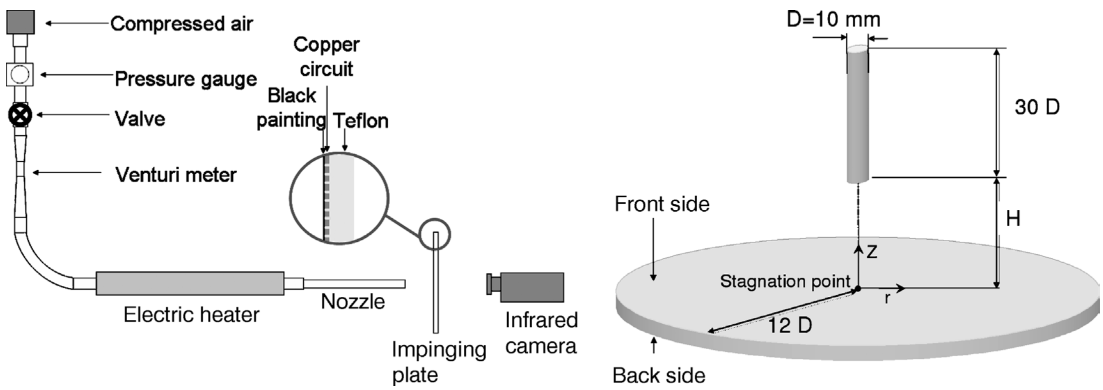


Fig. 1. Experimental apparatus.

Fig. 1. Dispositif expérimental.

and

$$\eta = (T_{ad} - T_{amb})/(T_j - T_{amb}) \quad (6)$$

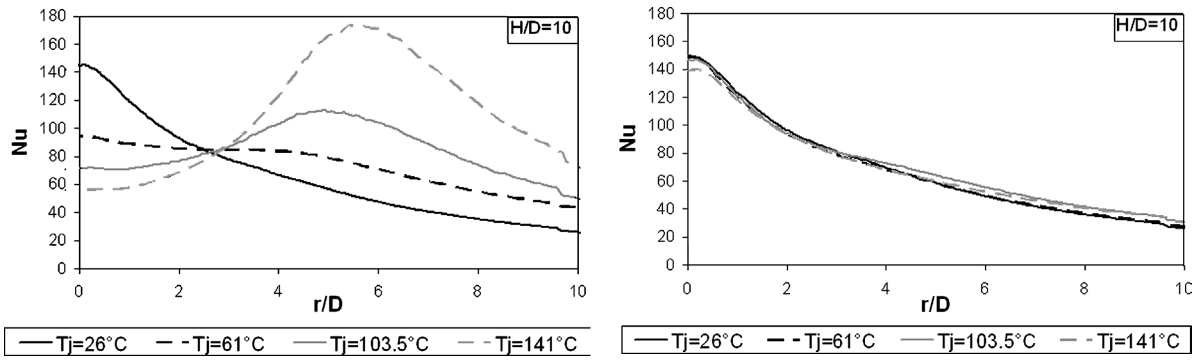
The random and global errors for the Nusselt number are less than 6% and 10% respectively. For the effectiveness, random and global errors are no more than 10% and 16%. All these errors are given for a trust interval of 95%.

4. Results

Correlation coefficients r^2 are superior to 0.99 indicating that the four couples (φ_{conv}, T_w) are aligned and validating this procedure. Representative examples of local Nusselt number distributions obtained for a given configuration with different injection temperatures are shown in Fig. 2 with T_j used as reference temperature in (a) and T_{ad} in (b). The collapse of the curves corresponding to different T_j in Fig. 2(b) confirms the result of the past investigations (Hollworth and Gero [2], Goldstein et al. [3]) and extends the injection temperature range up to 140 °C.

Thus, if T_{ad} is used as a reference temperature, Nusselt number distributions become essentially independent of the injection temperature. This means that entrainment of ambient air in the hotter jet can be taken into account with the effectiveness (which corresponds to dimensionless adiabatic wall temperature). Fig. 3(a) shows examples of effectiveness distributions for various T_j. These distributions do not depend on injection temperatures T_j. This means that entrainment effect is proportional to $(T_j - T_{amb})$ (Eq. (6)).

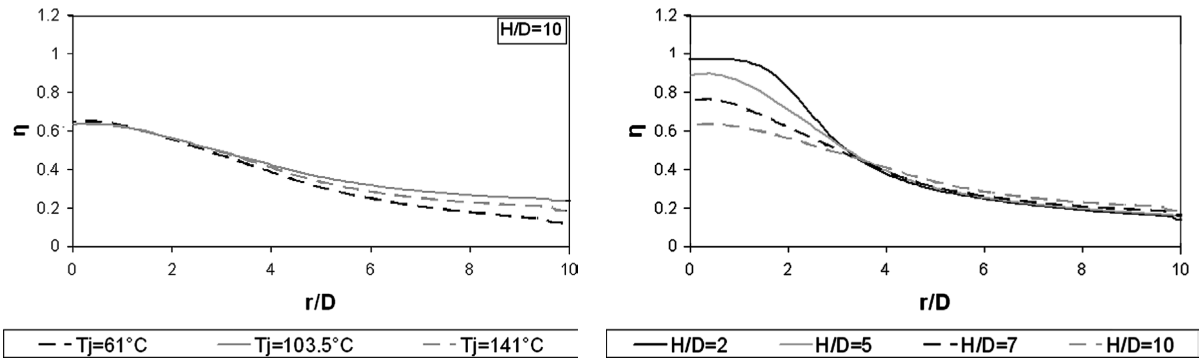
The various distributions are similar with a nearly constant effectiveness η near the stagnation point. For greater r/D, the effectiveness diminishes with increasing distance to the stagnation point. The explanation of this decrease is linked to the definition of T_{ad}. Adiabatic wall temperature is the temperature of the wall when there is no



(a) (b)

Fig. 2. Nusselt number distribution for $Re = 26\,500$ with: (a) $T_{ref} = T_j$, (b) $T_{ref} = T_{ad}$.

Fig. 2. Distribution du nombre de Nusselt pour $Re = 26\,500$ avec : (a) $T_{ref} = T_j$, (b) $T_{ref} = T_{ad}$.



(a) (b)

Fig. 3. Examples of effectiveness distribution for $Re = 26\,500$.

Fig. 3. Exemples de distribution de l'efficacité pour $Re = 26\,500$.

exchange between the wall and the jet, so T_{ad} is equal to the temperature of the jet close to the wall. Consequently, the effectiveness decrease corresponds to the reduction of the near wall flow temperature. There is also a drop of stagnation point effectiveness with increasing H/D (Fig. 3(b)). In fact, ambient cold air ($\approx 20\,^{\circ}\mathrm{C}$) penetrates into the hot jet by the large scale vortex structures convecting in the jet just after injection (these vortices are still present after the impingement), and the jet temperature is globally reduced by a process of ambient air entrainment.

5. Conclusion

A method based on the linear regression of (φ_{conv}, T_w) is proposed to study three temperatures problems and more precisely impinging jets with high injection temperature. Using this method, it is shown that the use of T_{ad} as reference temperature provides Nusselt number distributions which do not depend on the injection temperature up to $140\,^{\circ}\mathrm{C}$.

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