Blowing Effects on Heat and Mass Transfer for Different Geometrical Configurations

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ABSTRACT

In this paper, the blowing impact on the dynamical and thermal boundary layers is investigated through experiments and numerical simulations. Two different geometries (flat plate and circular cylinder) are separately studied. It is shown that blowing tends to thicken the boundary layers and to dramatically decrease the gradients in the immediate vicinity of the surface, leading to a strong decrease of the viscous stress and heat exchanges. Hence, the surface temperature can be lowered in case of cold blowing. This process finds applicability in the surface thermal protection area or in the flow control due to the modifications that blowing induces to the wake instabilities.

NOMENCLATURE

D	Diameter of the cylinder
f	Vortex shedding frequency
F	Injection rate $F = (\rho U_2)_{coolant}/(\rho U_1)_{main}$
Re	Reynolds number $Re = \rho U_e D/\mu$
Sr	Strouhal number $Sr = f\,D / U_e$
T	Temperature (K)
U	Velocity (m/s)
x	Spatial coordinate (m)
η	Effectiveness $\eta = \dfrac{T_e - T_w}{T_e - T_{inj}}$
μ	Dynamic viscosity (kg/m.s)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)

Subscripts

1	Longitudinal direction
2	Vertical direction
e	Main flow
inj	Injected flow
w	On the wall

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INTRODUCTION

For a long time already, the need for still further thermal protection of mechanical parts has triggered interest in the scientific community. Studies can be of both applied and fundamental nature. To further increase the gas turbines or ramjet effectiveness, a thermal protection of sensible parts must be provided. Different cooling techniques exist among which the discrete injection is one of the most popular (*e.g.* Carcasci & Facchini, 1996). Nevertheless, other techniques may be used such as blowing which we are interested in for our research activities. Our studies are concerned with heat and mass transfer within a boundary layer in case of blowing through the porous surface. The surface can be either a flat plate or a circular cylinder and studies are conducted in both an experimental as well as in numerical simulations manner. We take profit from a heated subsonic wind-tunnel at the lab (Bellettre *et al.*, 2000) and use the software package Fluent for simulations (Bellettre *et al.*, 1999 ; Mathelin *et al.*, 2000). In a first step, results from blowing through a flat plate are presented. Next, the blowing impact on the flow around a cylinder is addressed.

BLOWING THROUGH A FLATE PLATE

The blowing principles are presented in figure 1 :

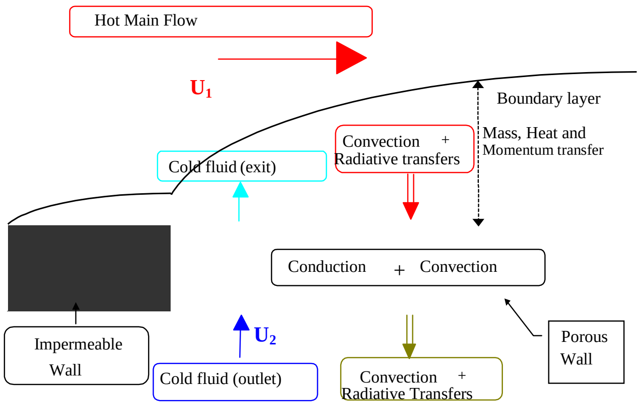

Fig. 1 – *Schematics of the blowing principles.*

A hot turbulent fluid flows on a porous flat plate through which a cool fluid (coolant) is injected. The amount of coolant is mesured in terms of blowing ratio defined as follows :

$$F = (\rho U_2)_{coolanrt} /(\rho U_1)_{main} \tag{1}$$

The main effect of the blowing onto the surface flow is to thicken the boundary layers, both dynamical and thermal. This becomes clearer with examination of figures 2 and 3 where a velocity profile within the boundary layer is plotted for both a non-blowing and a blowing case. The velocity field is computed with the use of the RNG k-ε model and the fluid injection through the surface is modeled (Bellettre *et al.,* 1999). Results issued from the simulations are compared to those from experiments upstream of the porous plate (with no injection) and at the middle of the plate (with injection). It can be observed on figure 2 that results from experiments (obtained with the use of Laser-Doppler anemometry) collapse with numerical simulations. In particular, the boundary layers thickenning is well reproduced with our model. The longitudinal velocity is also seen to dramatically decrease in the vicinity of the wall in case of injection. This velocity decrease induces lower fluid-surface friction stress.

The 100°C main stream temperature case is presented in figure 3 with the same blowing ratio as previously. Both coolant and solid part of the matrix temperatures are imposed and correspond to experimental data. Results presented in figure 3 show the good agreement between the numerical model and the experiment for thermal boundary layers upstream, as well as in the injection area. Notice the thermal boundary layer thickness is increased due to blowing and thus fluid temperature in the vicinity of the surface is lowered. This phenomenon leads to an important decrease in the convective heat exchanges between hot main fluid and cool surface: more than 80 % for a 1 % injection in our geometry.

Furthermore, blowing allows the wall temperature reduction by combining the protecting effects of boundary layer deviation and internal convective heat transfer within the porous matrix. This temperature reduction has been experimentally illustrated by wall temperature measurements (Bellettre *et al.*, 2000). The thermal protection effectiveness, η, is then defined as

$$\eta = \frac{T_e - T_w}{T_e - T_{inj}} \tag{2}$$

where T_e is the main flow temperature.

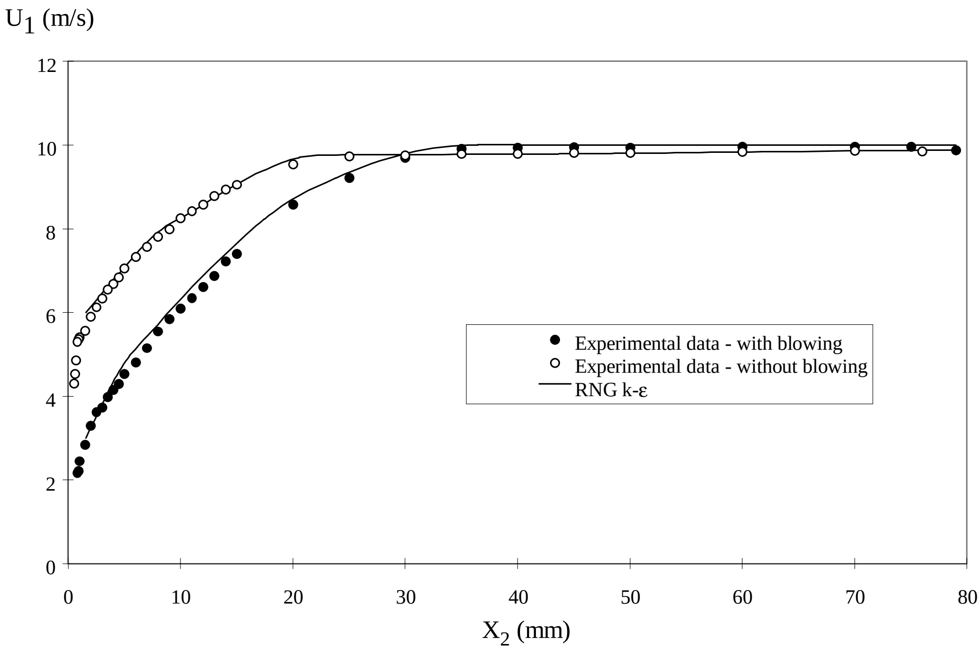

Fig. 2. – *Dynamical boundary layers upstream and in the injection area (F = 1 %).*

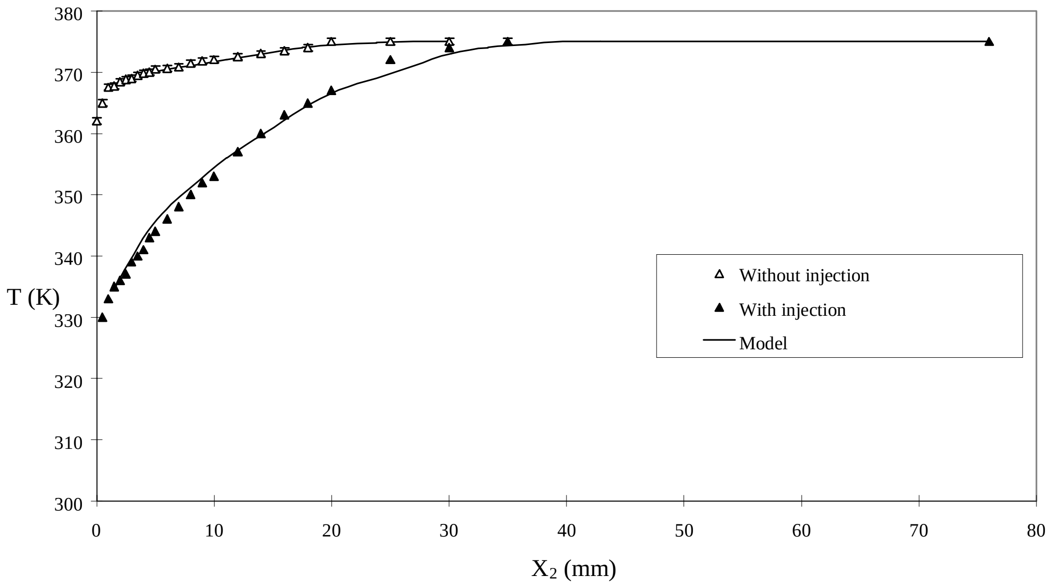

Fig. 3. – *Thermal boundary layers for a 100 °C main flow (F = 1 %).*

Figure 4 presents the thermal effectiveness evolution in the middle of the plate as a function of the injection rate for four different main flow temperatures. For strong blowing, all curves reach the same asymptotical value (97 %). Nevertheless, as the main flow temperature rises, the necessary injection rate to reach this asymptotical value increases. This is due to radiative heat transfer onto the porous wall: when the main flow becomes hotter, the radiative heat transfer from the hot surfaces within the wind tunnel increases and the porous wall thus requires higher injection rates for an effective thermal protection.

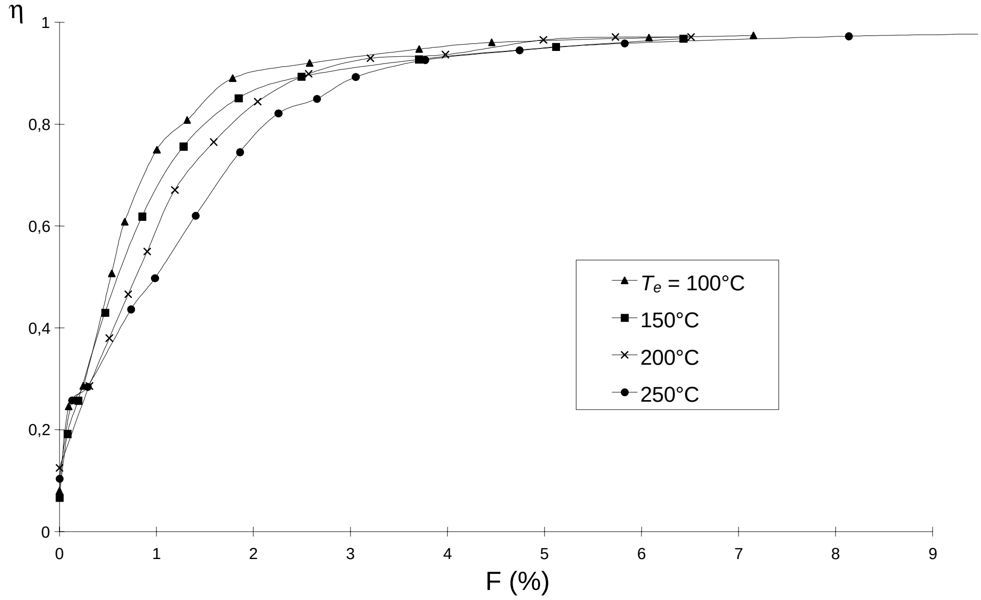

Fig. 4 – *Thermal effectiveness for different main flow temperatures.*

Finally, comparisons between blowing and discrete injection have been conducted. An example of protection using discrete injection through a slotted plate compared to a blowing case is shown in figure 5. This figure highlights a lower effectiveness in case of discrete injection. The differences have been studied on the mean and turbulent quantities, showing in all cases a much stronger impact in case of blowing compared to discrete injection.

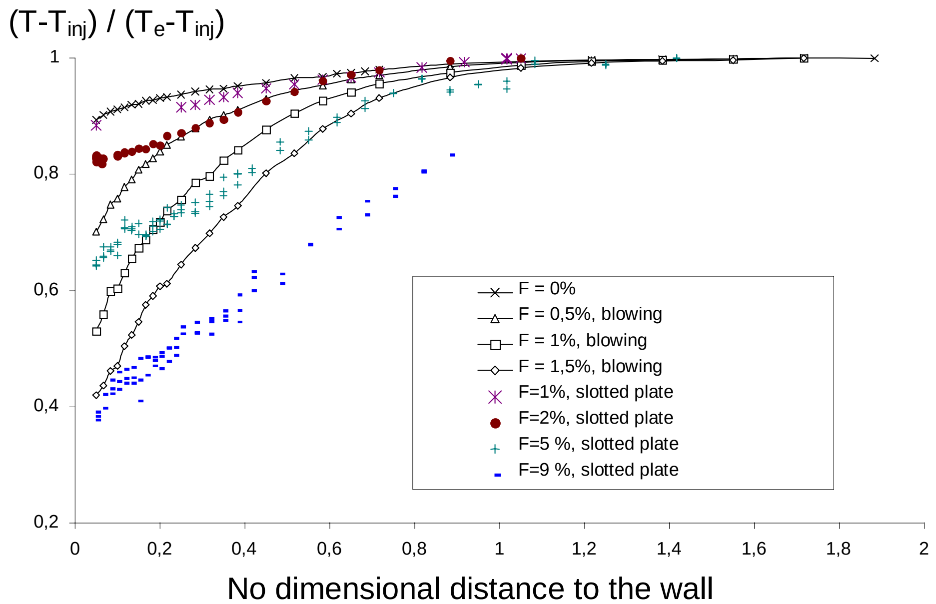

Fig. 5 – *Mean temperature profiles above the middle plane.*

BLOWING THROUGH A CIRCULAR CYLINDER

The cylindrical geometry, whose principles schematic is shown in figure 6, is chosen to get closer to configurations such as turbine blades or vanes. Consequently, it is worthwhile conducting a specific study of the blowing performances with this geometry.

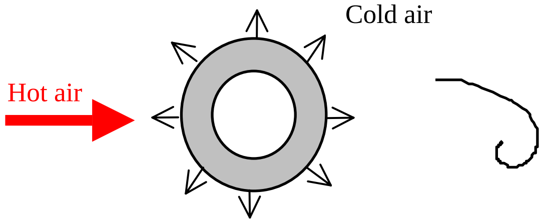

Fig. 6 – *Scheme of the cylinder configuration.*

In the range of Reynolds numbers considered here, $Re = \rho\, U_e D / \mu \in [3900 ; 31000]$, vortex shedding occurs at the rear of the cylinder and leads to the formation of the so called *von Karman vortex street* (see Williamson, 1996 for a comprehensive review of all related phenomena). The wake experiences periodic oscillations and a time average over several periods is necessary to get mean values. One can refer to Mathelin *et al.* (2001a) or Mathelin *et al.* (2001b) for further details on methodology and procedures.

In a similar fashion to the flat plate case, blowing tends to thicken the dynamical and thermal boundary layers (see figure 7). This increase in the thickness comes with a strong decrease of the gradients near the wall. Indeed, the viscous stress and the heat transfer coefficients lower when blowing becomes stronger.

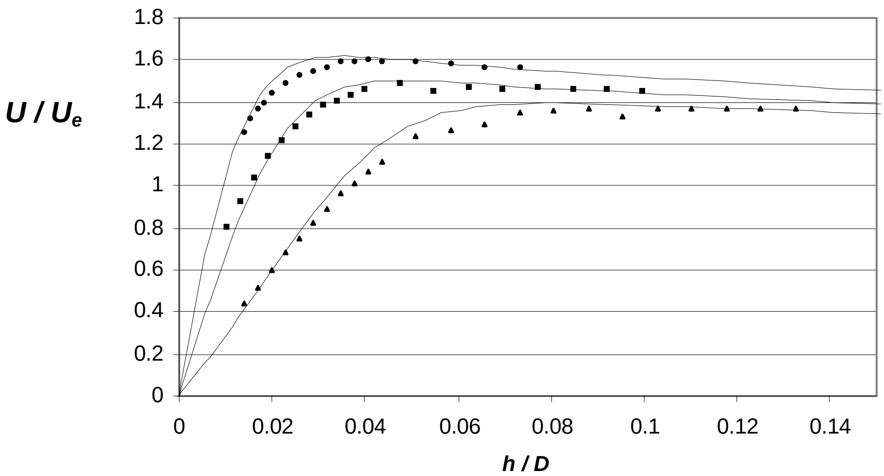

Fig. 7 – *Velocity magnitude vertical profile. Re =3900, angle of 65°. Symbols: experimental values; corresponding solid lines: numerical results.*
●, *F = 0 %*; ■, *F = 2 %*; ▲, *F = 5 %*.

The presence of a cold fluid layer in case of blowing isolates the wall from the main flow which can be hot. Figure 8 shows the thermal effectiveness evolution, as defined previously, with the blowing rate. For rates as low as 1 %, the wall temperature is already reduced approximately by a factor of 2. Applications cover a wide area, in particular for aeronautical turbine blades and vanes whose inlet temperature can reach temperatures as high as 600 K above the blade material melting point (see for example Facchini & Carcasci, 1996). It can also be noticed the good agreement between experimental values, measured by thermocouples welded directly onto the surface, and numerical simulations results, obtained using sources and holes models (Mathelin *et al.*, 2001a).

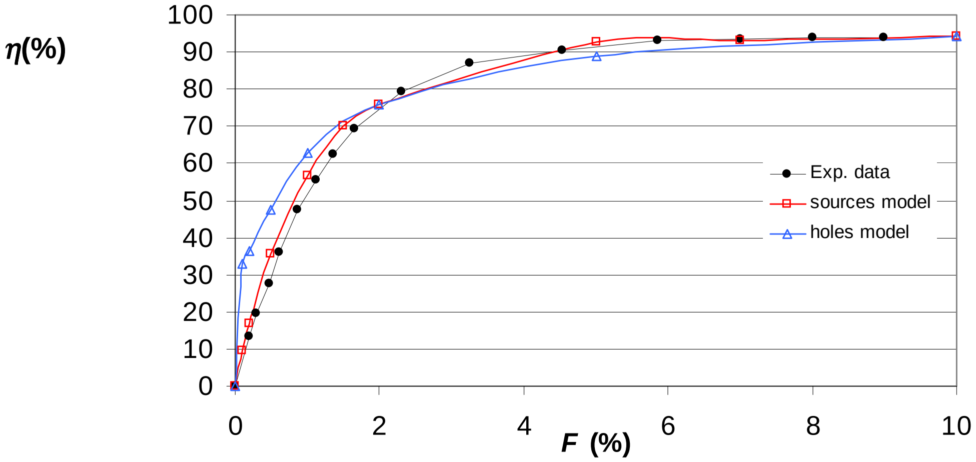

Fig. 8 - *Thermal effectiveness as a function of the blowing ratio. Re = 3900, T_∞ = 473 K, angle of 65°.*

The blowing also has an impact on the wake dynamics, which can lead to active wake control applications to be found (*e.g.* Roussopoulos, 1993 or Park *et al.*, 1994 among many others). The vortex formation region lengthens downwards, which results in a lower vortex shedding frequency. Figure 9 exhibits the adimensional oscillations frequency, expressed in terms of Strouhal number, $Sr = f\ D\ /\ U_e$, at a Reynolds number of 3900. The decrease of the Strouhal number remains at the same slope whatever the Reynolds number (Mathelin *et al.*, 2001c). It is approximately linear down to a saturation state for a 15 % injection, beyond which the vortex sheddings process decays.

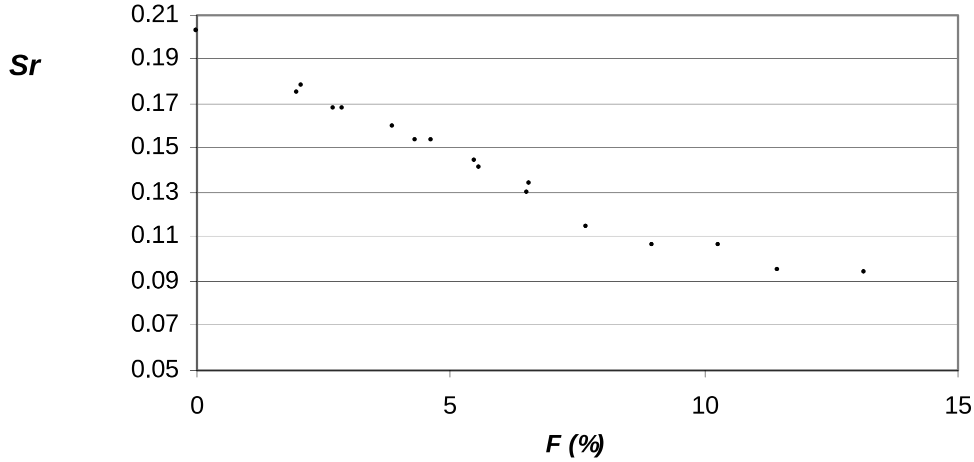

Fig. 9 - *Strouhal number as function of the injection rate.*
Re = 3900.

CONCLUSION

Influence of the blowing through a porous flat plate and a circular cylinder has been studied. Experimental and numerical results agree and show a thickenning of the boundary layers, both dynamical and thermal. The thermal protection effectiveness has been quantified for the two geometries and comparisons between discrete injection and blowing, in the case of the flat plate, were carried-out, showing a stronger impact of the latter. Finally, the blowing influence on the primary instability properties results in a decrease of the vortex shedding frequency.

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Name of Discusser: B. Simon, MTU Aero Engines Munich

Question:
Which application of your cooling method do you have in mind?

Answer:
Investigation of coking of porous materials with application to turbine blades and combustion chambers.

Name of Discusser: T. Arts, Von Karman Institute Rhode Saint Genese, Belgium

Question:
Can you explain the temperature measurements especially the sample frequency?

Answer:
Measurements with cold wire Frequency sample at 6 khz.