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Thermal study of a wall jet

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THE AIM of this work is to study a wall jet at the chosen velocity of 2 ms^{-1}, blowing above a metal plate in a wind tunnel; the Reynolds number based on the height of the convergent exit is 533. At the transition point of the flow, in the test section, a line heat source is located; it consists of a tungsten wire heated, electrically fixed to the wall plate, normally to the flow, and placed successively at three different heights above the plate. In the first phase, the wire was heated continuously: the temperature profiles obtained by a thermocouple showed a very rapid thermal diffusion. These temperature profiles are similar to turbulence rate profiles. The shift between the peaks which occurs is due to the partial absorption of the heat by the wall. In the second phase, the tungsten wire was heated intermittently by a quadratic signal and the thermal diffusion and the new velocity profile were studied considering the line heat source as the passive contaminant [1]. The study may have numerous applications for problems as: distribution of smoke leaving a chimney, heat transfer from a nuclear plant, effect of urban heating on the surroundings, heat transfer in certain installations of glass or steel works, meteorology (heat plumes).

W pracy przeprowadzono badanie strumienia przyściennego przepływającego z prędkością 2 ms^{-1} nad metalową płytą umieszczoną w tunelu aerodynamicznym. Liczba Reynoldsa, zdefiniowana dla wysokości na wyjściu z dyszy, wynosiła 533. W punkcie przejściowym badanego obszaru umieszczono liniowe źródło ciepła (drut wolframowy ogrzewany elektrycznie) umocowane równolegle do płyty i prostopadle do kierunku przepływu. Źródło to było kolejno przemieszczane w trzech położeniach ponad płytą. W pierwszej fazie, drut ogrzewano w sposób ciągły: profile temperatury mierzone za pomocą termopary wykazywały bardzo szybką dyfuzję termiczną. Profile te były podobne do profili natężenia turbulencji. Przesunięcie między maksimami pojawiało się wskutek częściowej absorpcji ciepła przez ściany. W drugiej fazie, drut ogrzewano w sposób przerywany, sterowany sygnałem: dyfuzję termiczną i nowe profile prędkości badano przyjmując, że liniowe źródło ciepła jest biernym elementem zaburzającym [1]. Przeprowadzone badania mogą mieć liczne zastosowania w zagadnieniach: rozkładu dymu opuszczającego komin, przenoszenia ciepła z zakładów nuklearnych, wpływu ogrzewania miast na otoczenie, przenoszenia ciepła w niektórych instalacjach hut stali lub szkła oraz meteorologii.

В работе исследуется околостенный поток, протекающий со скоростью 2 мс$^{-1}$ над металлической пластиной, помещенной в аэродинамическом тунеле. Число Рейнольдса, описанное для высоты на выходе сопла, составляло 533. В точке перехода исследуемой области, был помещен линейный источник тепла (провод из тугстенита, обогреваемый с помощью электроэнергии), закрепленный параллельно над пластиной и под прямым углом к направлению течения. Этот источник перемещался поочередно по трём направлениям над пластиной. В первой фазе провод обогревался непрерывно: температурные профили измерялись с помощью термопары и выявили очень быструю термодиффузию. Эти профили были подобны до профилей интенсивности турбулентности. Несовпадение максимальных значений появлялось вследствие частичной абсорбции тепла стенкой. Во второй фазе провод, подогревался с перерывами, управляемыми сигналами: термическая диффузия и новые профили скорости в предположении, что линейный источник тепла является пассивным возмущающим элементом [1]. Проводимые исследования могут найти многочисленное применение в задачах: распределения дыма, выходящего из трубы, переноса тепла, но предприятиях использующих внутриядерную энергию влияния ТЭУ городов на окружающуюсреду, переноса тепла в некоторых устройствах на металлургических и стекальных заводах, а также в метеорологии.

1. Introduction

STUDIES concerning turbulent boundary layer in the presence of a line source of heat have been made. P. PARANTHOËN and M. TRINITE [1], D. J. SCHLIEN and S. CORRSIN [2] have studied the influence of a source, supposing that the flux is zero on the wall. M. BELORGEY and M. TRINITE [3] have considered that in a turbulent boundary layer, the conditions of the wall have some influence on the temperature profiles. G. F. MARSTERS, B. HOWKINS and E. KORTSHAK [4] have studied the influence of a heated wall jet above a plate simulating a heated ventilated plane jet coming from an engine compressor and hitting aircraft flaps. Wall temperature distributions and temperature profiles in the flow field are reported. NGUYEN ANH DUNG [5] has brought a contribution to the heat transfer study in a turbulent boundary layer when there exists a line heat source. We applied digital technics allowing instantaneous and simultaneous velocity and temperature measurements.

But there does not seem to be as yet a study of a wall jet in the presence of a heat line source.

2. Apparatus and procedure

A wind tunnel (Fig. 1) supplies a wall jet at a low velocity by a fan with a maximum flux of 0.25 $m^3 s^{-1}$. The upstream part of the exit nozzle is furnished with a honey comb and different filters to laminarize the jet. The convergent exit is 30 cm wide and 0.4 cm high. The test section is 30 cm high and is made of a metal plate 120 cm long as basis, and of three plexiglass walls. A Cartesian support allows the displacement of the hot

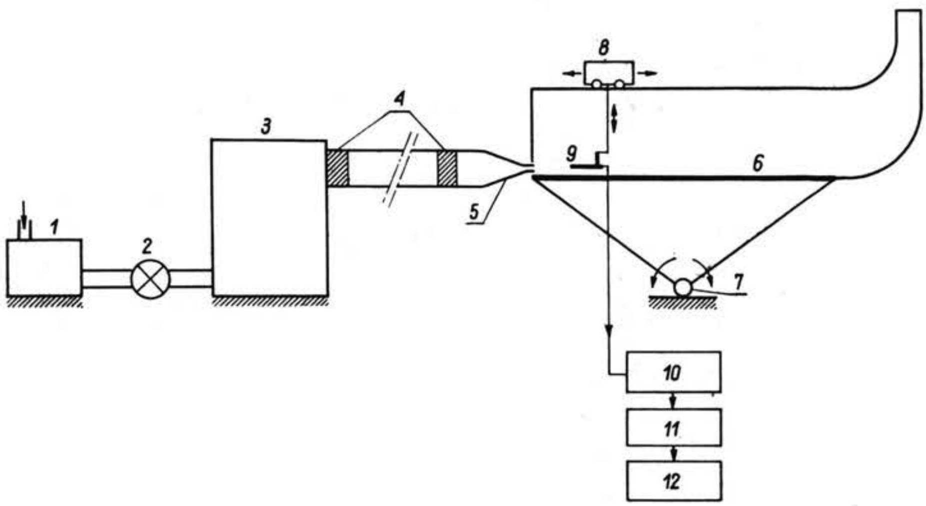

FIG. 1. Wind tunnel. *1* — fan, *2* — valve, *3* — settling chamber, *4* — honey comb, *5* — nozzle, *6* — metal plate, *7* — support, *8* — hot wire support, *9* — hot wire, *10* — anemometer, *11* — integrator, *12* — voltmeter.

wire and the thermocouple in the vertical symmetry plane with a precision of 0.1 mm. The preturbulence of the flow is in the range 0.3% at the chosen velocity of 2 ms^{-1}.

The transition zone where the line source is located, begins at a distance from the convergent exit equal to ten times its height h_s. The source consists of a tungsten wire of a length of 30 cm, parallel to the base plate and normal to the flow (Fig. 2). In the first phase this wire (diameter $d = 100\ \mu$) is heated electrically by a direct current continuously. The power dissipated by the wire varies from 70 to 80 watts/m according to its location with respect to the jet. In the second phase this tungsten wire is heated intermittently with the same power as in the previous case by applying an on/off signal of a two-second period. The velocity measurements were made by a calibrated (DISA) hot wire anemometer along the plate [6].

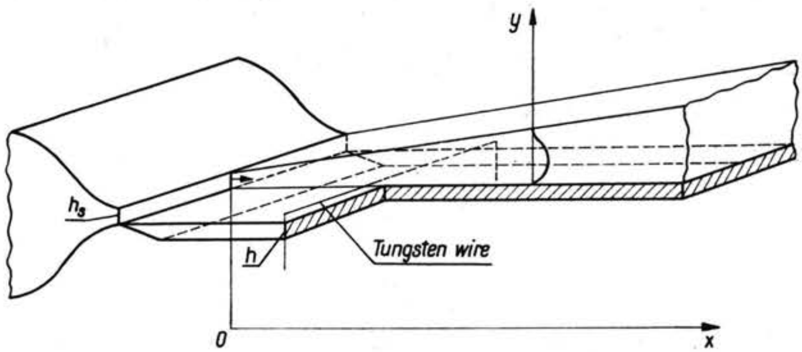

FIG. 2. Plane wall jet.

The mean temperature measurements were made by a manganine-constantan calibrated thermocouple with copper connection wires, of a diameter 1/10 mm. A continuously working recorder gives temperature variations.

Experiments were realized for three different heights above the plate

$$\frac{h}{h_s} = 0.375, \quad \frac{h}{h_s} = 0.75, \quad \frac{h}{h_s} = 1.75.$$

3. Influence of the temperafure of a wall jet on velocity profiles

The presence of a tungsten wire located in a transition zone and heated by the Joule effect changes the temperature of the wall jet above the plate. We may conclude that the ambient temperature T_a in the test section is modified in function of the heat dissipation around the tungsten wire; the measurements of velocity profiles by a hot wire anemometer must then be compensated for ambient temperature variations.

3.1. The overheating temperature

The hot wire is heated to a certain temperature T_f called overheating temperature. Let b be the temperature coefficient of the electric resistance of the hot wire; we can write the hot resistance as

$$R_f = R_a + b_1 R_a (T_f - 293), \tag{3.1}$$

R_a being the cold resistance of the wire, we have

(3.2) $$R_f = (1+s)R_a,$$

s being the overheating coefficient

$$T_f = 293+s/b_1.$$

For a platinum wire

$$b_1 = 3.6\times 10^{-3}\ \mathrm{K}^{-1}.$$

In our case $s = 0.7$ and $T_f = 487.44$ K.

3.2. Correction of the velocity for temperature variations

Let us write the King law connecting the velocity u to the tension V at the ends of the hot wire

$$R_f I^2 = V^2 = R_f(T_f-T_a)\left(A+B\sqrt{u}\right),$$

I being the overheating intensity.

A and B are given by the expressions

(3.4) $$A = 0.42\frac{\pi\lambda}{b_1 R_a}\, lP_r^{0.20},$$

(3.5) $$B = 0.57\frac{\pi\lambda}{b_1 R_a}\, lP_r^{0.33}\left(\frac{d}{\nu}\right)^{0.5},$$

λ — being the thermal conductibility, l — being the hot wire length, P_r — being the Prandtl number, d — being the diameter of the wire.

We can also write

(3.6) $$\mathscr{A} = AR_f(T_f-T),$$

(3.7) $$\mathscr{B} = BR_f(T_f-T).$$

The values of A and B are known by the calibration of the hot wire (V^2 plotted as a function of $\sqrt{u}$).

In our case we find

$$R_f = 8\Omega \quad \text{or} \quad t = 20°\mathrm{C}, \quad \mathscr{A}_a = 3.8\ \mathrm{V} \text{ and } \mathscr{B}_a = 2.2\ \mathrm{V.s.m^{-1}}.$$

Let t_a°C be the ambient temperature = 19°C or $T_a^0 = 292\ \mathrm{K}^{-1}$, so we can write the King law as

(3.8) $$(R_f I)^2 = (V^2)_a = R_f(T_f-T_a)\left(A+B\sqrt{u}\right).$$

We suppose that T_g is the mean temperature at a given point when the tungsten wire is heated. We can know T_g by temperature profiles obtained by the thermocouple measurements.

REID and SHERWOOD [7] give the relationship connecting λ and ν to the temperature T:

(3.9) $$\frac{\lambda_{fm}(g)}{\lambda_{fm}(a)} = \left(\frac{T_{fm}(g)}{T_{fm}(a)}\right)^{0.75},$$

(3.10) $$\frac{\nu_{fm}(g)}{\nu_{fm}(a)} = \left(\frac{T_{fm}(g)}{T_{fm}(a)}\right)^{1.75},$$

with

$$T_{fm}(g) = \frac{T_f+T_g}{2},$$

$$T_{fm}(a) = \frac{T_f+T_a}{2}.$$

For the same value of the tension V, the value of the velocity depends on the temperature.

So for two temperatures T_a and T_g we can write from Eqs. (3.8) and (3.9)

$$R_f(T_f-T_a)\left(A_a+B_a\sqrt{u_a}\right) = R_f(T_f-T_g)\left(A_g+B_g\sqrt{u_g}\right).$$

The value of the velocity u_g at the temperature T_g is then

$$u_g = \left(\frac{\mathcal{A}_a+\mathcal{B}_a\sqrt{u_a}-\mathcal{A}_g}{\mathcal{B}_g}\right)^2$$

and so

$$\mathcal{A}_g = \left(\frac{T_f-T_g}{T_f-T_a}\right)\times\mathcal{A}_a\times\left(\frac{T_{fm}(g)}{T_{fm}(a)}\right)^{0.75},$$

$$\mathcal{B}_g = \left(\frac{T_f-T_g}{T_f-T_a}\right)\times\mathcal{B}_a\times\left(\frac{T_{fm}(g)}{T_{fm}(a)}\right)^{0.125}.$$

In our case we have

$$\mathcal{A}_a = 3.8\ \mathrm{V}, \qquad \mathcal{B}_a = 2.2\ \mathrm{V.s.m^{-1}},$$

$$T_f = 487\ \mathrm{K}, \qquad T_a = 293\ \mathrm{K}.$$

We can conclude that it is possible to know the exact value of the velocity at a given point above the plate by a correction which takes account of the variation of temperature of the wall jet at this point. In fact, we need the value of the velocity for an ambient temperature of 20°C corresponding to the calibration of the hot wire and the local mean temperature for the same point to obtain the exact velocity profile.

4. Results

4.1. Temperature profiles

We have chosen different positions located along the plate and established temperature profiles perpendicular to the plate for three separate heights of the heating tungsten wire. We have measured the temperature difference between the local mean temperature T_g and the ambient mean temperature T_a of 293 K. All data are reported with respect to the height of the convergent exit h_s.

4.1.1. Wire is continuously heated with a power

$= 78$ W/m for $h/h_s = 0.375$,

$= 80$ W/m for $h/h_s = 0.750$,

$= 70.4$ W/m for $h/h_s = 1.75$.

In fact, this power varies according to the position of the tungsten wire with respect to the flow which produces a resistance variation. We obtain maximum temperature variations of about 10°C and we can see in Fig. 3 that the thermal dissipation is very rapid. We have observed two peaks for every profile except for the points near the heat line source.

4.1.2. When the tungsten wire is heated intermittently by a quadratic signal of period of two seconds with the same power as the continuous heating, we obtain a maximum

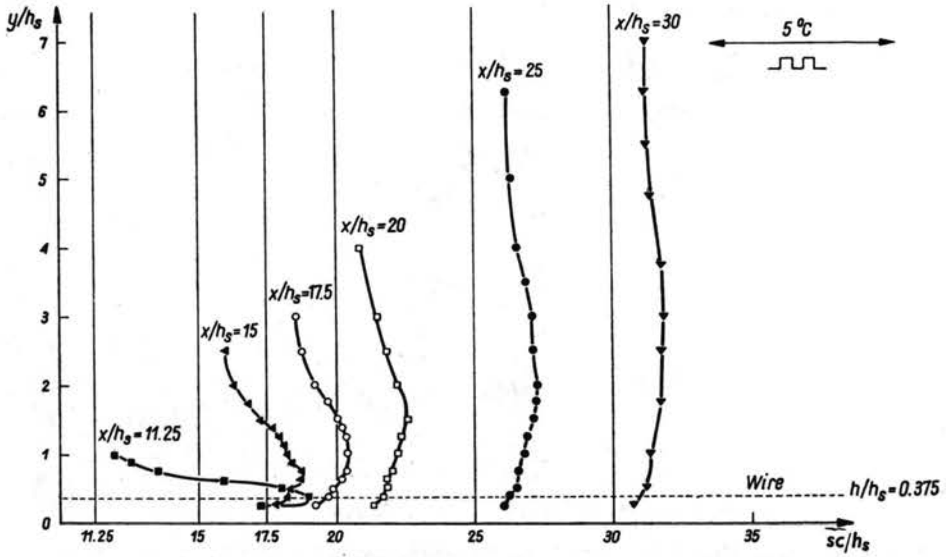

FIG. 3. Temperature profiles with continuous heating.

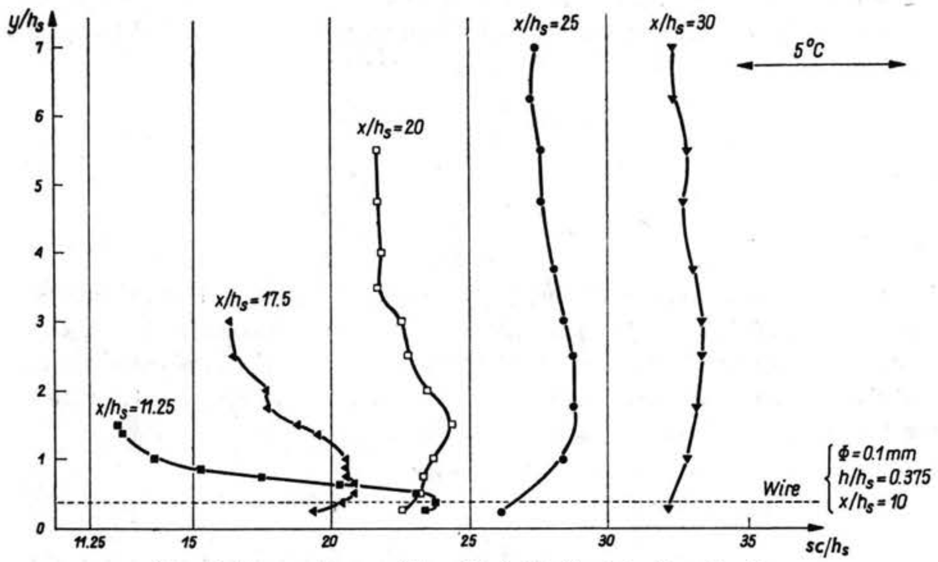

FIG. 4. Temperature profiles with intermittent heating $T = 2$ s.

of about 6°C (Fig. 4) that represents slightly more than half of the maximum obtained by continuous heating; this is due to the thermal inertia. When we compare these temperature profiles with the curves giving the turbulence rate curves (Fig. 5), we note that their behaviour is identical except in the neighbourhood of the heating line source. In fact, the peaks of the turbulence rates correspond approximately to the temperature peak. The shift which exists is due to the fact that a part of the heat is absorbed by the plate. Doing the energy balance, we can see that a part of the heat dissipated by the Joule in the tungsten wire is absorbed by the wall (33% for $h/h_s = 0.375$, 20% for $h/h_s = 1.75$). We also remarked in the figure that the thermal dissipation was very rapid.

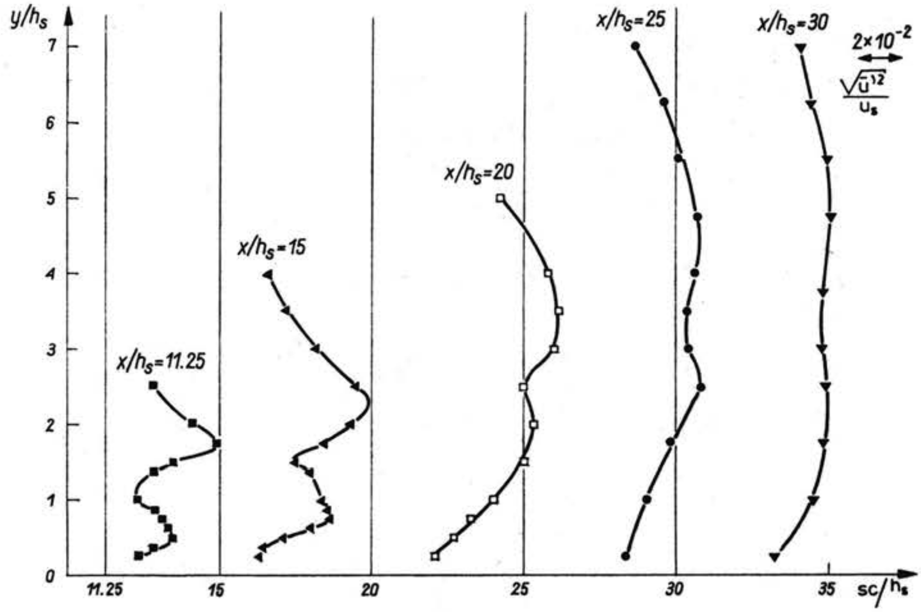

FIG. 5. Turbulence rates $\sqrt{\bar{u}'^2}/u_s$.

4.2. Velocity profiles

We made a vertical exploration along the plate with the hot wire anemometer at the same points as for temperature profiles. First we made a series of profiles without a tungsten wire and then in the presence of the unheating tungsten wire (Fig. 6). Comparing these velocity profiles, we can conclude that the dynamic perturbation is negligible; in the vicinity of the wire it remains within 5%.

From the velocity profiles obtained at 293 K and from the temperature profiles, we calculated the new velocity profile taking account of the local mean temperature in the presence of an intermittent heating. We used the correction based on the REID and SHERWOOD formula (§ 3). We chose four abscissas for three different heights of the tungsten wire (Fig. 7).

Comparing the results with velocity profiles obtained without heating, we concluded that for $h/h_s = 0.375$ the profile are slightly modified by the presence of the heat line

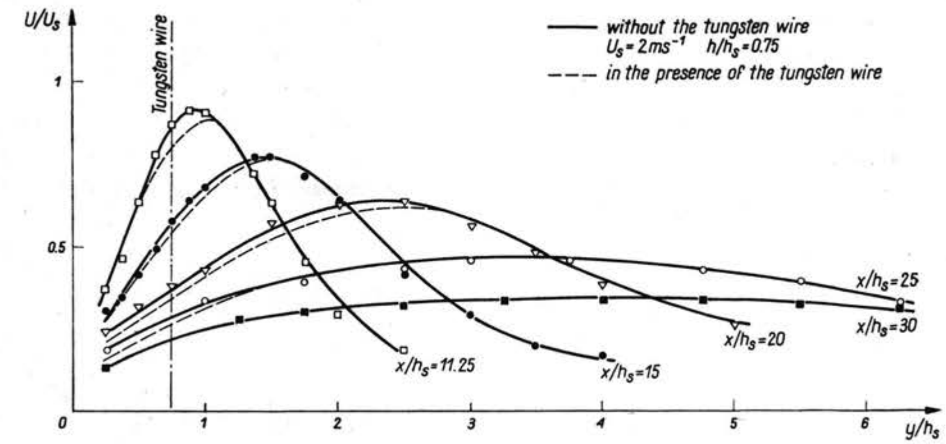

FIG. 6. Velocity profiles.

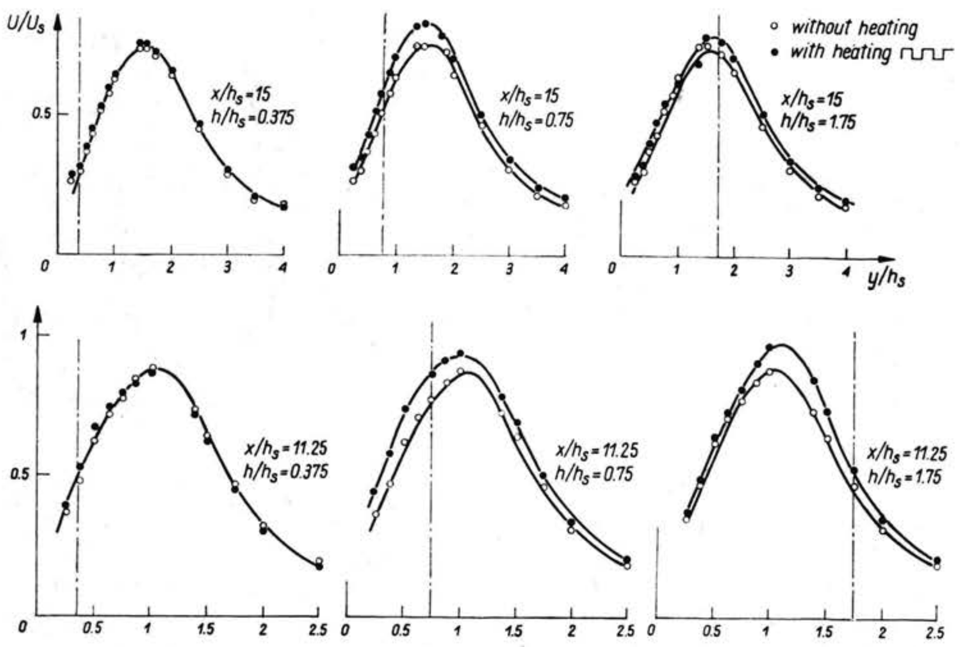

FIG. 7. Corrected velocity profiles.

source because a third of the energy is absorbed by the wall. For two other heights: $h/h_s =$ $= 0.75$ and $h/h_s = 1.75$, we could see that the maximum perturbation is of the order of 8%, which is small.

4.3. Evaluation of the flux rates

We made a tentative of experiments to obtain the mass flux rates based on the mass flux rate at the exit of the convergent,

$$q/q_0 = \int_0^\infty \varrho u dy / \varrho_\infty u_\infty h_s$$

with and without the heat tungsten wire for 4 abscissas in Fig. 8. We took account of the correction of the velocity due to the temperature variations and the variation of ϱ with the temperature

$$\varrho = \varrho_\infty (1 - \Delta T/273).$$

Without heating the jet we can see that the mass flux rate grows up with the abscissa and reaches a maximum for $x/x_h = 30$. When the tungsten wire is heated by a quadratic signal, the mass flux rate grows up a little (10%) more. It would be interesting to study what exactly occurs at the free boundary of the jet in the presence of heat transfer.

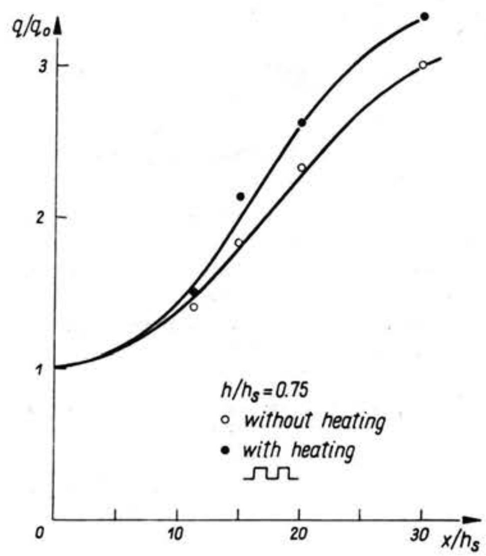

FIG. 8. Mass flow rates.

5. Conclusion

A thermal and dynamical study of the wall jet has been realized in a wind tunnel giving a wall jet above a metal plate in the presence of a line source heated either continuously, or intermittently by a quadratic signal of a period of 2 s. The temperature profiles obtained showed that the thermal dissipation was very rapid. These profiles generally present two peaks whose behaviour is similar to the turbulence rates profiles with a shift depending on wall heat absorption more or less important according to the location of the heat line source. The maximal temperature fluctuations are about 10°C for a continuous heating and 6°C for an intermittent one. The heat line source is considered as passive contaminant.

We then studied the consequences of this thermal dissipation on the dynamic behaviour of the jet. Velocity profiles were set up with the Reid and Sherwood hypothesis according to which λ and ν depend on T in the King law. The velocity difference between the case without heating and the case with intermittent heating was about 8%. It would be interesting to pursue the study with intermittent signals of different forms and periods and to study the thermal and dynamic behaviour of the wall jet in the presence of these heat line sources.

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