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FREE CONVECTION COEFFICIENT ENHANCEMENT BETWEEN INCLINED WALL AND AIR IN PRESENCE OF EXPIRED JETS

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ABSTRACT

This paper aims to determine the heat transfer enhancement in natural convection between a downward-facing inclined wall, heated by Joule effect, and air in the presence of small air pulsating expired jets, in conditions of medium temperature difference between wall and air, namely 40K. Experimental measurements have been taken both with and without pulsating expired jets. The wall is kept in condition of uniform temperature. The expired jets blow out perpendicularly from the wall surface. An infrared thermo-camera was used to check the wall temperature uniformity. Hot-wire anemometer and visualization with smoke were used to find information on the air velocity field.

The wall inclination angle which maximizes the convective heat exchange near the leading edge has been investigated too.

INTRODUCTION

First, Pohlhausen [1] and other researchers [2-3] have studied natural convection heat transfer from vertical walls to air both theoretically and experimentally. Recently some investigations have shown the opportunity of a considerable enhancement of heat transfer by means of fins and pins, namely by passive devices [4-8]. Since 1980 Schlichting [9] has studied the enhancement by means of devices which require energy consumption: he investigated the influence of the aspiration, and recently Ligrani [10-12] and Alì [13], evidenced the influence of transpiration. All these studies, specifically the theoretical ones which are based on the boundary layer theory, refer to moderate temperature differences between the fluid and the plate, i.e. a few degrees or 20K at the most. On the contrary, the current literature does not offer references about the use of jets for destabilizing the boundary layer on a inclined wall in natural convection. Recently, some tests with a vertical wall have been perfomed at the Department of Energetics of Pisa [14-17].

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In this research, we have measured the heat transfer enhancement due to the influence of the expired jets in conditions of a temperature difference of 40K between an inclined aluminum wall, heated by Joule effect, and air.

The variables taken into account for the heat transfer coefficient optimization are the following with expired jets:

Time interval when the jets are inactive, T off;
Time interval when the jets are active T on;
exit velocity of the jets, v;
number of active jets arrays;
wall inclination angle downward.

NOMENCLATURE

h	[W/m^{2}K]	Average convection coefficient
h_L	[W/m^{2}K]	Local convection coefficient
I	[A]	Electrical current
k	[W/mK]	Thermal conductivity
$\dot{Q}_{L.conv.}$	[W]	Local convection heat flow
$\dot{Q}_{L.Joule\ eff.}$	[W]	Local heat flow by Joule effect
$\dot{Q}_{L.frt.rad.}$	[W]	Local heat flow by front radiation
$\dot{Q}_{L.bck.cond.}$	[W]	Local heat flow by back conduction
S	[m^2]	Area
T_a	[K]	Air temperature
T_{on}	[s]	Jets activity time
T_{off}	[s]	Jets inactivity time
T_w	[K]	Wall temperature
q	[W/m^2]	Heat flux
v	[m/s]	Air jet velocity

V	[V]	Voltage drop

Subscripts

A	Air
W	Wall
L	Local

EXPERIMENTAL APPARATUS

The experimental apparatus consists of the aluminum wall (1200 x 600mm^2), of thickness 6 mm fixed to a support in order to remain in the vertical or inclined position (Figure 1). Three vertical lines (spaced out 160 mm) of eleven holes, 1.5 mm in diameter, have been made in the central part. They are spaced out 100 mm from each other. An alternative compressor pushes the air out of the holes.

The air jets are regulated by an electrovalve, controlled by an electronic circuit to determine the time intervals when the jets are active or inactive. Forty eight adhesive electrical resistances (100 x 150mm^2) are applied to the wall inner side and regulated by converters.

In the back there are two insulating layers with thickness 40 mm and conductivity k = 0.04 W/mK. Wall thermocouples, connected to a multimeter, are positioned both on the outer and inner surfaces and between the insulating layers. All the data are acquired by a personal computer. The temperature uniformity (with differences of about 0.3K) is obtained by regulating the variacs which supply electrical power to the thermo-resistances. The uniformity is checked by means of an AVIO Neo Thermo TVS-600 infrared video camera.

A layer of lexan is placed under the aluminum wall, with other small jets, lined up with the previous ones, to increase the local convection coefficient in the lower zone.

EXPERIMENTAL PROCEDURE

First we activate the jets and, changing the dissipated electrical power, we re-establish the previous temperature uniformity.

This procedure is performed because non-uniform temperature produces conduction heat transfer along the wall that cannot be accurately calculated.

The temperature uniformity is obtained regulating the variacs that are connected to the adhesive electrical resistances on the wall central part.

The procedure for every experimental test, fixed the wall downward inclination angle, is as follows:

1) the initial temperature measured by means of the 8 thermocouples must be the same with an error of +/- 0.3K
2) we impose a temperature difference between wall and air of 40K for all the tests;
3) the measured temperatures must remain constant, to assure steady state conditions both at the beginning and at the end of each test;
4) then the electrical power dissipated on the resistances is measured according to the previous conditions;
5) the room temperature is 298K;

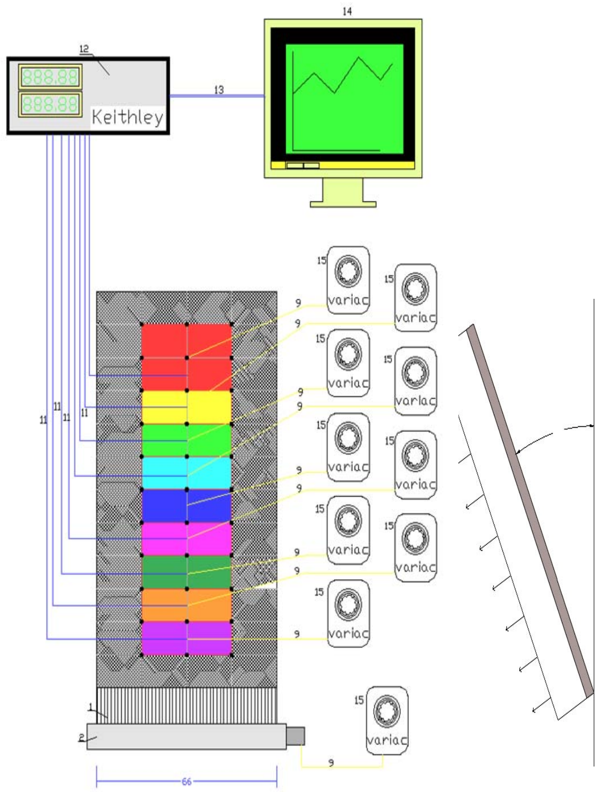


Figure 1. Experimental set-up: frontal and lateral view

6) the new convection coefficient in the presence of the jets is calculated utilizing the mean temperature value and the local dissipated electrical power.

In order to maximize the heat transfer coefficient, all the tests have been focused on the optimization of the following parameters:

Active horizontal lines of jets;
jets activity time, T on;
jets inactivity time, T off;
active air jets exit velocity, v.

ANALISYS OF UNCERTAINTIES IN EXPERIMENTAL RESULTS

The local coefficient of convection is computed with the equation

$$h_L = \frac{\dot{Q}_{L.conv.}}{(T_w - T_a)S} \qquad (1)$$

with $\dot{Q}_{L.conv.} = \dot{Q}_{L.Joule\ eff.} - \dot{Q}_{L.frt.rad.} - \dot{Q}_{L.bck.cond.}$ which means that the local convection heat flow is obtained subtracting, from the local electrical power, the heat flow lost by front radiation and the one transmitted by conduction on the back side. Taking into account all the uncertainty sources and adopting the procedure described by Moffat [18], the maximum error in h_L was estimated as less than 12.5%.

In facts:

$$\dot{Q}_{L.Joule\ eff.} = v\ i$$

the average error on both *v* and *i* is 2.5%, then the total error is the sum: 5.0%;

$$\dot{Q}_{L.frt.rad.} = B(T_w^4 - T_a^4)$$

the average error for T_w is 0.5%, then for T_w^4 is 2%; the average error for T_a is 1%, then for T_w^4 is 4% and, according to the sum error rule, the total error for radiation heat flow is 6%;

$$\dot{Q}_{L.bck.cond.} = (T_w - T_i)/C$$

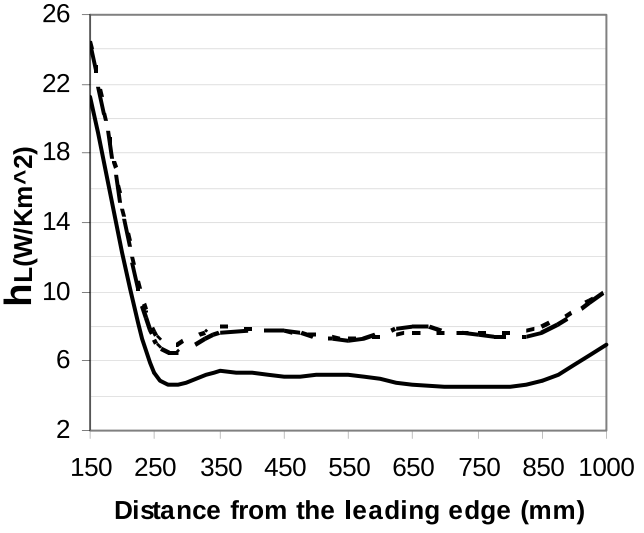
the average error for T_w is 0.5%; the average error for T_i is 0.5%, then according to the sum error rule, the total error for conduction heat flow is 1.0%.

The local convection heat flux total error is 11.0%. In conclusion the precision of the local heat transfer coefficient defined by equation (1), since numerator and denominator relative errors are dependent, is their sum: 12.5%.

EXPERIMENTAL RESULTS

Vertical wall with ΔT=40K

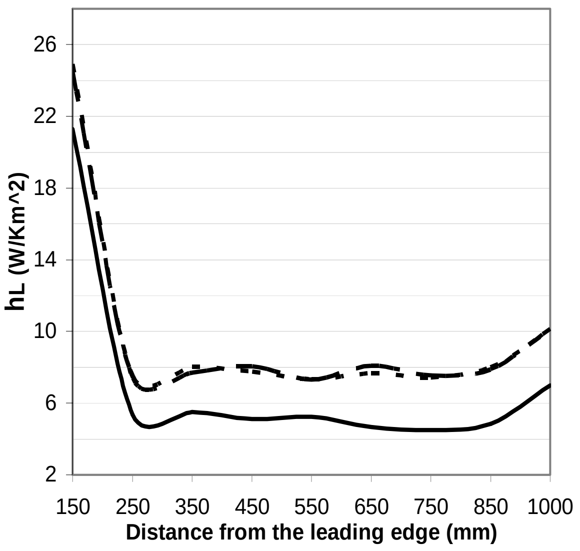
All the tests have evidenced that the pulsating expired jets are more efficient than the continuous ones: in particular, in the most favorable conditions, the heat transfer coefficient increases of 52% (form 5.0 to 7.6 W/m^2K) with respect to the case without jets. If we exclude the case with all the jets activated, for considerations of energy saving, the horizontal lines of jets producing the best conditions have been the 3rd on the lexan wall and the 1st on the aluminum one.



—— without jets - - -jets 3/1 Ton=Toff=0.5s, v=25.3 m/s, -- -- -- -jets 3/1 Ton=1s, Toff=0.5s, v=25.3 m/s

Figure 2: Local convection coefficient vs. distance from the leading edge for different expired jets activity and inactivity times, ΔT=40K and v= 25.3 m/s, in the case of a vertical wall.

This configuration is indicated in the paper as 3/1. The activity and inactivity times of the jets to maximize *h* have been, respectively, T on=0.50s and T off=0.50s (Figure 2 and 3) but the differences are smaller than the experimental error. The air outlet velocity maximizing *h* has been 53.1m/s, that is the maximum value performed: in fact, as Figure 4 shows, the trend of the average convection coefficient vs. the jets exit velocity is asymptotic. For this reason it is not convenient to use a velocity higher than 12m/s.



—— without jets - - -jets 3/1 Ton=Toff=0.5s, v=53.1 m/s

-- -- -- -jets 3/1 Ton=1s, Toff=0.5s, v=53.1 m/s

Figure 3: Local convection coefficient vs. distance from the leading edge for different activity and inactivity times of the jets, with ΔT=40K and v=53.1 m/s, in the case of a vertical wall.

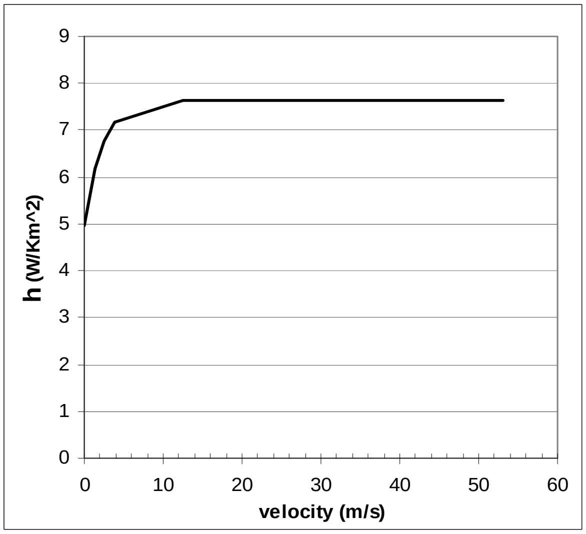
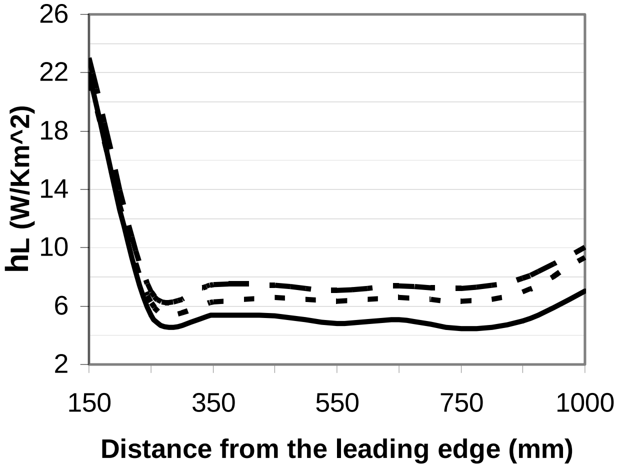


Figure 4: Average convection coefficient vs. jets exit velocity with ΔT=40K in the case of a vertical wall.

By means of the hot wire anemometer test, it is possible to show that the transition between the laminar and the turbulent regime occurs at a distance of 750 mm from the wall bottom: this is in agreement with the theoretical correlation [8].

5 degrees downward inclined wall, with ΔT=40K

Without jets, the average convection coefficient is the same as the one of the vertical position. The experimental tests have shown that the pulsating jets are more efficient than the continuous ones: in particular, in the most favorable conditions, the heat transfer coefficient increases of 54% with respect to the case without jets.



—— without jets – – –jets 3/1 Ton=Toff=0.5s, v=1.2 m/s

-- -- -- -jets 3/1 Ton=Toff=0.5s, v=12.5 m/s

Figure 5: Local convection coefficient vs. distance from the leading edge for different jets velocity, with ΔT=40K and 5 degrees of wall inclination.

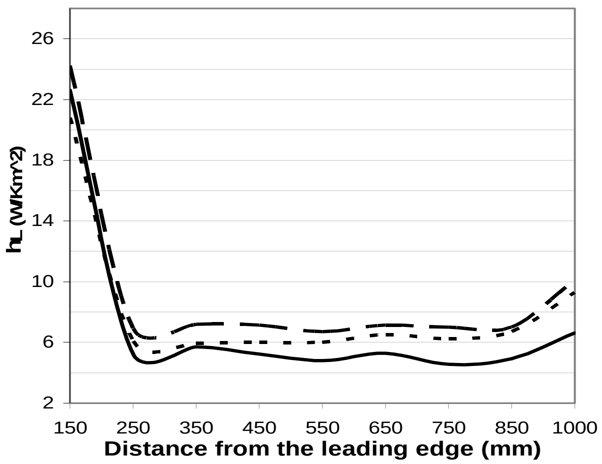
If we exclude the results with all the activated jets for considerations of energy saving, the horizontal line of jets producing the best conditions has been again the 3/1(Figure 5).

The activity and inactivity times of the jets to maximize *h* have been T on= Toff =0.50s: but the differences with the other time combinations relative to the expired jets are small in comparison with the experimental error.

11 degrees downward inclined wall, with ΔT=40K

In these experimental tests we verified that the horizontal lines of most effective jets, except for the totality of them, have been the 3rd on the lexan wall and the 1st on the aluminum one.

Also in this case the choice of inactivity and activity time of jets does not significantly affect *h*. The most convenient value of the velocity is equal to 12.5 m/s (Figure 6) and it produces an increase of average heat transfer coefficient (in the central part of the wall) of 38% (from 5.3 to7.3W/m^2K).



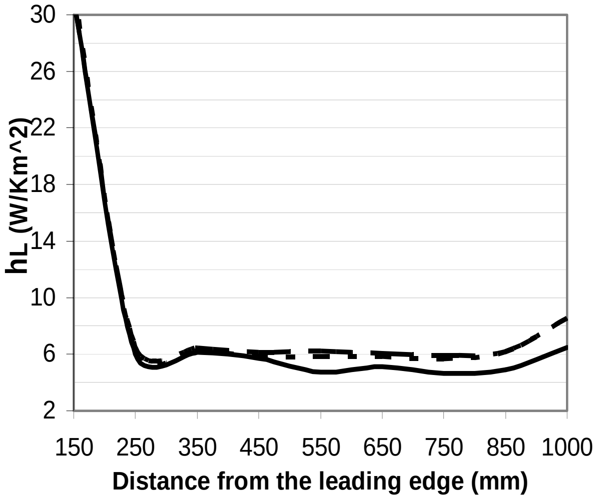
—— without jets – – –jets 3/1 Ton=Toff=0.5s, v=1.2 m/s

-- -- -- -jets 3/1 Ton=Toff=0.5s, v=12.5 m/s

Figure 6: Local convection coefficient vs. distance from the leading edge for different jets velocity, with ΔT=40K. and 11 degrees of wall inclination.

22 degrees downward inclined wall with ΔT=40K

The horizontal lines of most effective jets, except for the totality of them, have been the 3rd on the lexan wall and the 1st on the aluminum one. Also in this case the choice of inactivity and activity time of jets does not significantly affect *h*.



—— without jets – – –jets 3/1 Ton=Toff=0.5s, v=1.2 m/s

-- -- -- -jets 3/1 Ton=Toff=0.5s, v=7.5 m/s

Figure 7: Local convection coefficient vs. distance from the leading edge for different active expired jets velocity, with ΔT=40K and 22 degrees of wall inclination.

The most convenient value of the expired jets velocity is equal to 7.5 m/s (Figures 7 and 8) and it produces an increase of average heat transfer coefficient of 26% (from 5.3 to 6.7W/m^{2}K) .

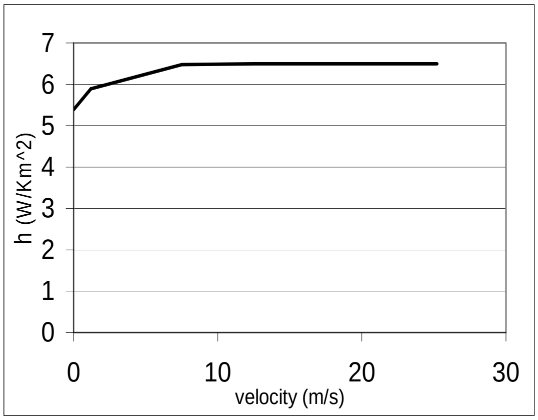


Figure 8: Trend of heat transfer coefficient vs. velocity for a 22 degrees inclined wall.

In this case too, the pulsated jets are more efficient then the continuous ones (+18%), but changing the activity and inactivity times of the jets, the differences in *h* are lower then the experimental error: for this reason we assume Ton = Toff=0.50s.

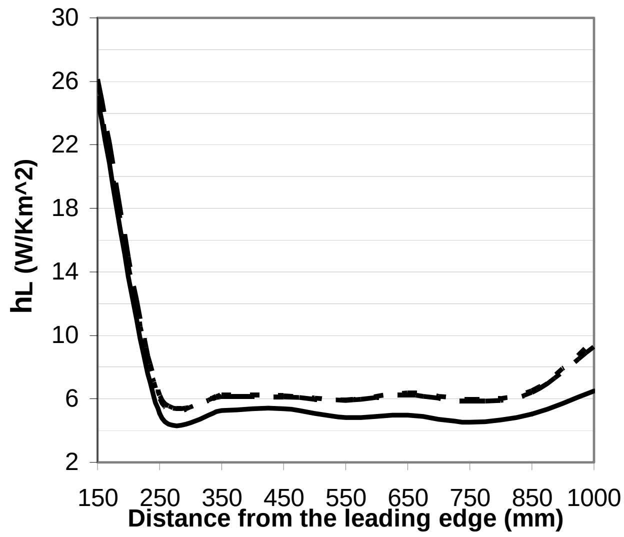
25 degrees downward inclined wall, with ΔT=40K

In these experimental tests we verified that the horizontal lines of most effective jets, except for the totality of them, have been once more the 3rd on the lexan wall and the 1st on the aluminum one. Also in this case the choice of inactivity and activity time of jets does not significantly affect *h*. The optimal velocity is equal to 12.5 m/s (Figure 9) and it produces an increase of average heat transfer coefficient (in the central part of the wall) of 24%(from 5.0 to 6.2W/m^{2}K).

ANALYSIS OF RESULTS AND CONCLUSION

Without jets, in the proximity of the leading edge, the local heat transfer coefficient increase up to an inclination angle of 22 degrees, then it decreases (Figures 10 and 11). That can be explained by the visualization obtained with smoke. In fact, Figure 12 shows that, with an inclination angle of 22 degrees, the boundary layer thickness at 150mm from the leading edge is about 50% of the one relative to the vertical wall. The boundary layer reduction is probably due to the vertical buoyancy forces that push the air against the inclined wall (Figure 12).

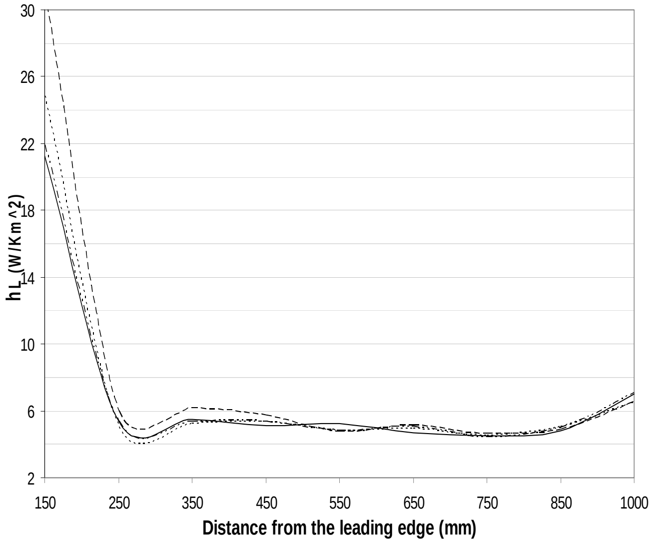
In presence of active jets, if we exclude the case with all the jets activated, for considerations of energy saving, the horizontal lines of jets producing the best conditions have been the 3rd on the lexan wall and the 1st on the aluminum one in all the cases. The effect of the activity and inactivity times up to 1 second, in downward inclined walls is negligible; then we assume the time T on=T off=0.5s. With a wall downward inclination of 5 degrees we have not found differences from the vertical case on the heat transfer coefficient.



— without jets - - -jets 3/1 Ton=Toff=0.5s, v=1.2 m/s

-- -- -- -jets 3/1 Ton=Toff=0.5s, v=12.5 m/s

Figure 9: Local convection coefficient vs. distance from the leading edge for different active expired jets velocity, with ΔT=40K and 25 degrees of wall inclination.



— vertical wall, – ¨ – 5 degrees downward inclined wall — — 22 degrees downward inclined wall - - - - 25 degrees downward inclined wall

Figure 10: Local convection coefficient vs. distance from the leading edge for different wall inclination angles without jets and ΔT=40K

The optimal jets velocity is 12.5 m/s and the increase of *h* is about 54 %. If we incline downward the wall of 11 degrees, the trends of *h* at different velocities are closer than in the previous case.

The increase of *h* with the optimal velocity of 12.5 m/s fell down to 38%. If the wall inclination is 22 degrees, the increase of heat transfer coefficient results 26% and the local heat transfer trends at different velocities are almost coincident. If we incline the wall downward of 25 degrees , the asymptotic value of *h* is 6.2 W/m^{2}K and it is sufficient an outlet velocity of the jets of 1.2 m/s: in this case the increase of *h* is about 23%.

Concluding, if the downward angle wall inclination increases the influence of the jets on heat transfer enhancement decrease, due to the competing role of buoyancy.

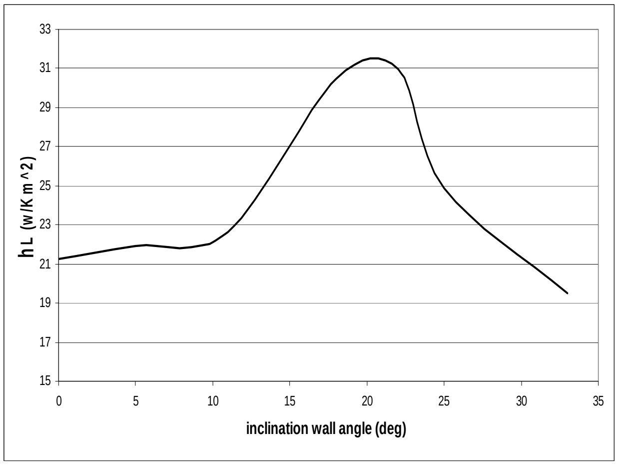


Figure 11: Local convection coefficient at 150mm from to the leading edge vs. downward inclination wall angle, with ΔT=40K and no expired jets.

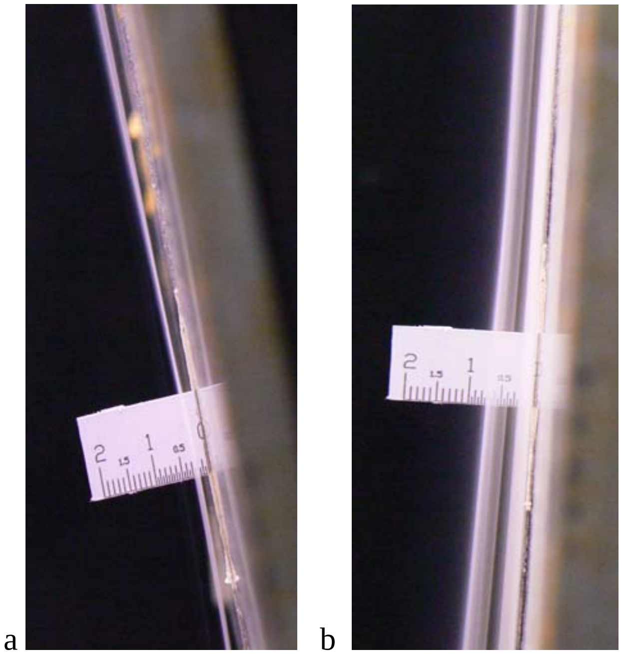


Figure 12: Boundary layer thickness at 250 mm from the leading edge a) 22 degrees inclined wall; b) vertical wall.

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