

HEAT TRANSFER ENHANCEMENT BETWEEN VERTICAL WALL AND AIR IN PRESENCE OF EXPIRED OR ASPIRED JETS: COMPARISON BETWEEN FREE AND MIXED CONVECTION CONDITIONS

Bartoli Carlo
Department of Energetics,
University of Pisa,
Pisa, 56126,
Italy,
E-mail: c.bartoli@ing.unipi.it

ABSTRACT

This keynote lecture aims to determine the heat transfer enhancement in natural and in mixed convection between a vertical wall, heated by Joule effect, and air in the presence of small air pulsating aspirated and expired jets, in conditions of medium and large temperature differences between wall and air, namely from 25 to 70K. Experimental measurements have been taken both with and without pulsating and continuous expired and aspirated jets. The expired jets blow out perpendicularly from the wall surface. A thermo camera was used to ensure the wall temperature uniformity. A hot wire anemometer and visualization with smoke were used to found information about the air velocity field. The parameters which maximize the convective heat exchange have been computed.

The present research represents a first step of a basic study to optimize the turbine behavior cooled by pulsating jets.

INTRODUCTION

Since 1921, Pohlhausen [1] and many researchers [2-3] have studied natural convection heat transfer from vertical walls to air both theoretically and experimentally. Recently some investigations have evidenced the possibility of a considerable enhancement of heat transfer by means of fins and pins, namely by passive devices [4-8].

Twenty years ago Schlichting [9] have studied the enhancement by means of devices which requires energy consumption: in particular he investigated the influence of the aspiration, and recently Ligrani [10-12] and Ali [13], evidenced the influence of transpiration.

All these studies, specifically the theoretically 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 as maximum 20K.

On the contrary, the current literature offers a very small number of references about the use of jets for destabilizing the boundary layer on a vertical wall in mixed convection condition.

The present work represent the conclusion of an experimental activity, co-funded by the Ministry of the University and Scientific Research and by the University of Pisa, about free and mixed convection performed during the last for years at the Department of Energetics "L. Poggi" of the University of Pisa [14-17].

In this research, we have measured the heat transfer enhancement due to the influence of the expired and aspirated jets in conditions of medium and large temperature differences between a vertical aluminum wall, heated by Joule effect, and air, namely from 25 to 70K. Both aspiration and expiration are performed intermittently through small holes.

The variables taken into account for to optimize the heat transfer coefficient are the following both with aspirated and expired jets:

- 1) period of time when the jets are inactive, T off;
- 2) period of time when the jets are active T on;
- 3) exit velocity of the jets, v;
- 4) number of active jets arrays.

In the optimization conditions and for free convection a general enhancement of the total heat transfer coefficient of about 80% can be achieved.

Instead the experimental tests in mixed convection evidence optimal results those indicate that the presence of destabilizing jets can modestly increase the convective heat transfer coefficient (+37%) even in the best conditions.

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 600mm²) fixed to a support in order to remain in the vertical 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 or a vacuum pump suck it up.

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. Adhesive electrical resistances are applied to the wall inner side and regulated by converters.

Then 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.

In free convection a layer of lexan is placed under the aluminum wall, with other small jets to increase the local convection coefficient in the lower zone.

Instead in mixed convection a tangential fan supplies a steady air flux placed under the aluminum wall, that establish the mixed convection.

EXPERIMENTAL PROCEDURE

First we have activated the jets and, changing the dissipated electrical power, we have re-established 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 has been as follows:

- 1) the initial temperature measured by means of the 8 thermocouples must be the same with an error of +/- 0.3K;

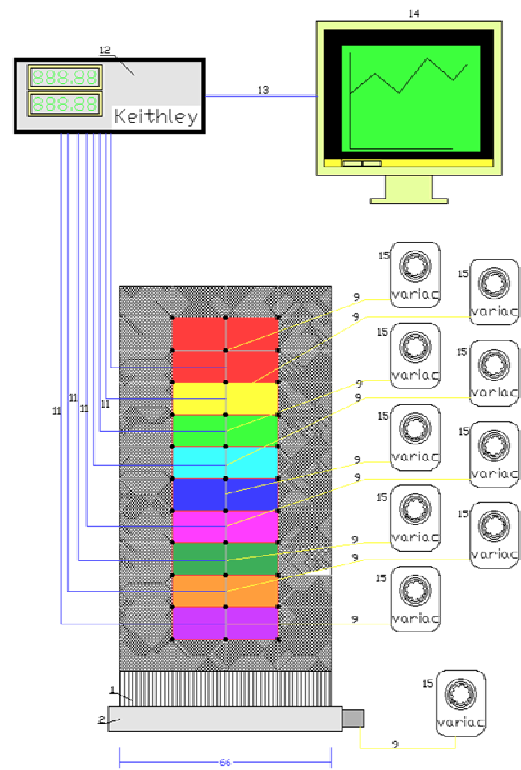


Figure 1. Experimental set-up in mixed convection: frontal view.

- 2) we impose a temperature drop between wall and air of 25, 40, and 70K, respectively, in three series of experimental 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 has been 25K;
- 6) the new convection coefficient in the presence of the jets has been 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.

ANALYSIS OF UNCERTAINTIES IN EXPERIMENTAL RESULTS

The local coefficient of convection is computed with the equation

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

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, $\dot{Q}_{L.Joule\ eff.} = v i$ and 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_a^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 radiation 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 the equation (1) since numerator and denominator relative errors are dependent is their sum: 12.5%.

FREE CONVECTION EXPERIMENTAL RESULTS

Expired jets with $\Delta T=25K$

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 more than 80%.

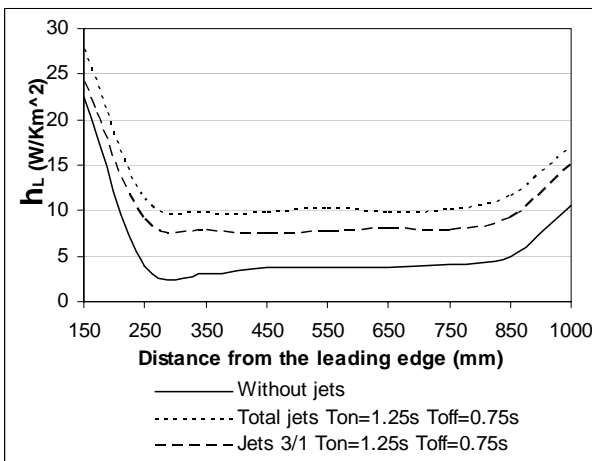


Figure 2: Local convection coefficient vs. distance from the leading edge for different active expired jets configurations, with $\Delta T=25K$ and $v=8.7m/s$.

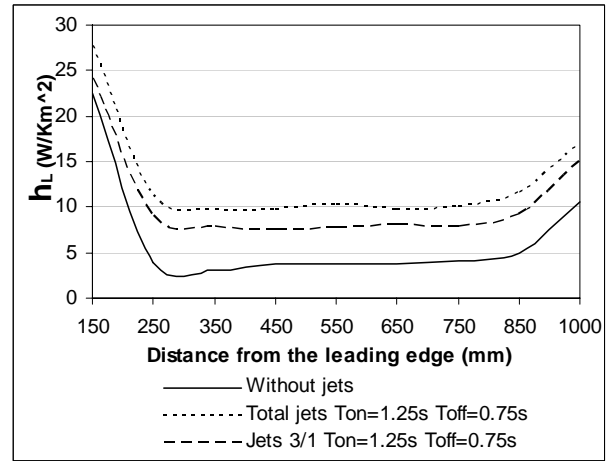


Figure 3: Local convection coefficient vs. distance from the leading edge for different active expired jets configurations, with $\Delta T=25K$ and $v=8.7m/s$.

The optimal air exit velocity has been 8.7m/s (Figure 2). The activity and inactivity times of the jets to maximize h have been, respectively, $T_{on}=1.25s$ and $T_{off}=0.75s$.

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. This configuration is indicated in the paper as (3/1) (Figure 3). The transition between the laminar and the turbulent regime occurred at a distance of 790 mm from the wall bottom: that occurred where h_L increase on the right of diagram. This agrees with the theoretical correlation of Bejan and Cunningham [8].

Aspirated jets with $\Delta T=25K$

The experimental tests have shown that the aspirated pulsating jets are more efficient than the continuous ones: in particular, in the most favorable conditions, the heat transfer coefficient increases more than 55%.

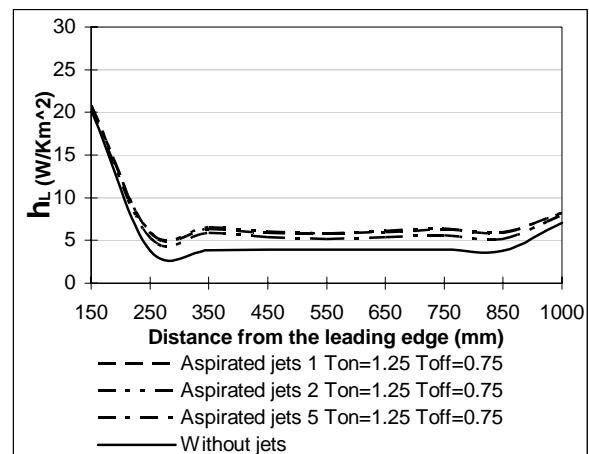


Figure 4: Local convection coefficient vs. distance from the leading edge for different configurations of active aspirated jets, with $\Delta T=25K$ and $v=8.7m/s$.

If we exclude the results with all the jets activated for considerations of energy saving, the horizontal line of jets

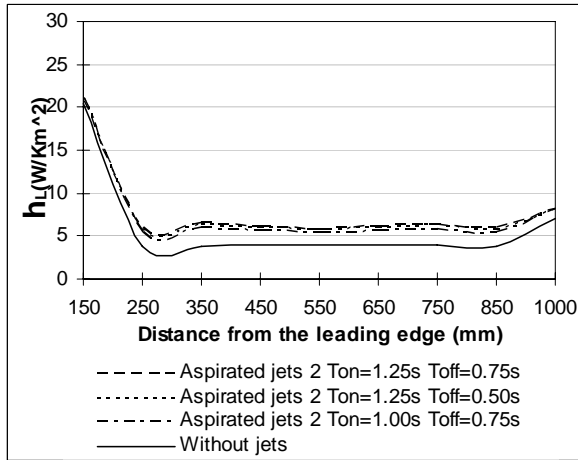


Figure 5: Local convection coefficient vs. distance from the leading edge for different times of aspirated jets activity, with $\Delta T=25K$ and $v=8.7m/s$.

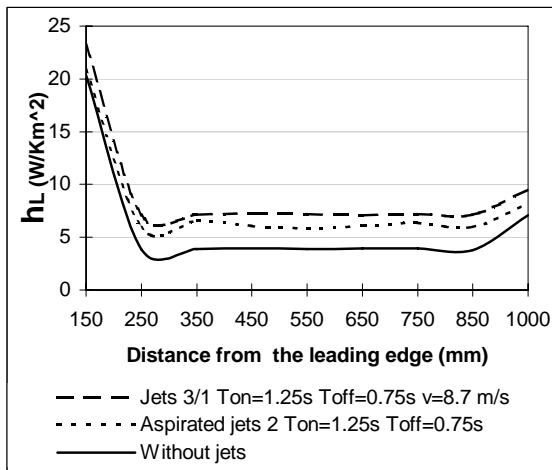


Figure 6: Comparison between local convection coefficient vs. distance from the leading edge for the best configurations with expired, aspirated and without jets, with $\Delta T=25K$.

producing the best conditions has been the 2nd on the aluminum wall. This configuration is indicated in the tests as 2 (Figure 4).

The activity and inactivity times of the jets to maximize h have been, respectively, $T_{on}=1.25s$ and $T_{off}=0.75s$: this is the same time combination relative to the expired jets (see Figure 5).

The comparison between the behavior local heat transfer coefficient with expired and aspirated jets shows that the first ones are more efficient at $\Delta T=25K$ (Figure 6).

Expired jets with $\Delta T=40K$

The optimal air exit velocity has been 8.7m/s: this is the same value as the previous case relative to a temperature drop of 25K (Figure 7). The activity and inactivity times of the

jets to maximize h have been, respectively, $T_{on}=0.50s$ and $T_{off}=0.50s$ (Figure 8).

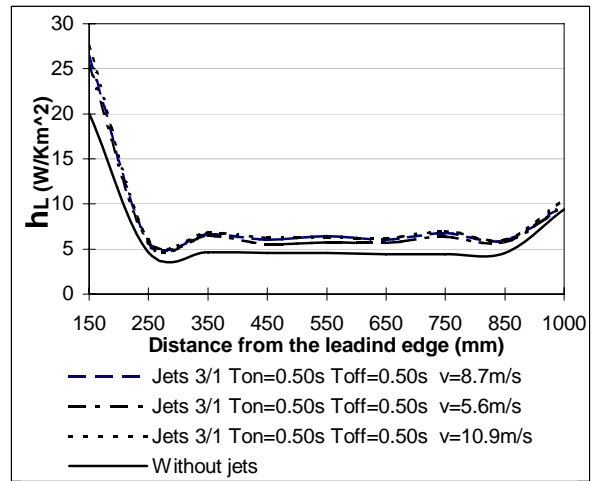


Figure 7: Local convection coefficient vs. distance from the leading edge for different configurations of active jets, with $\Delta T=40K$.

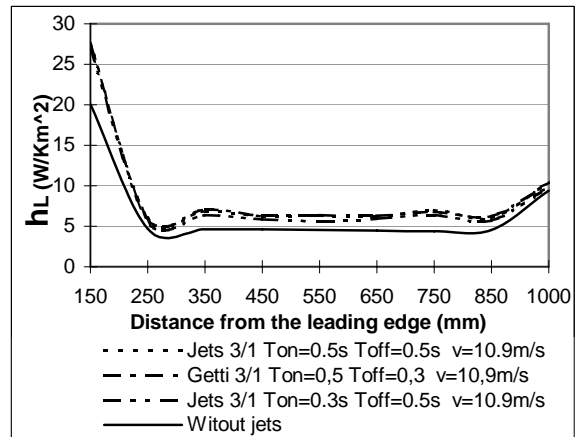


Figure 8: Local convection coefficient vs. distance from the leading edge for different activity and inactivity times of the jets, with $\Delta T=40K$.

If we exclude the results 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: configuration (3/1).

This set-up is less efficient than the previous one with $\Delta T=25K$: in facts, in the most favorable conditions, the global heat transfer coefficient increases a little more than 40% ($h=6.4W/m^2K$). This is about one half of the value corresponding to a temperature drop of 25K. By means the hot wire anemometer test it is possible to evidence that the transition between the laminar and the turbulent regime occurred at a distance of 750 mm from the wall bottom: this is in agreement with the theoretical correlation [8].

Aspirated jets with $\Delta T=40K$

The experimental tests have shown that the aspirated pulsating jets are more efficient than the continuous ones: in

particular, in the most favorable conditions the heat transfer coefficient increases more than 65% with respect to the case without jets.

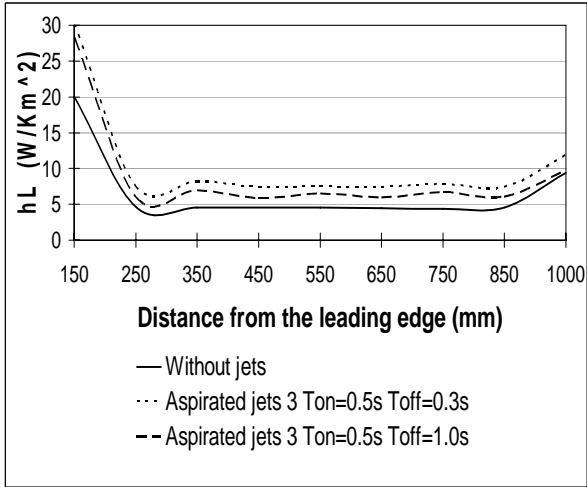


Figure 9: Local convection coefficient vs. distance from the leading edge for different configurations of active aspirated jets, with $\Delta T=40K$.

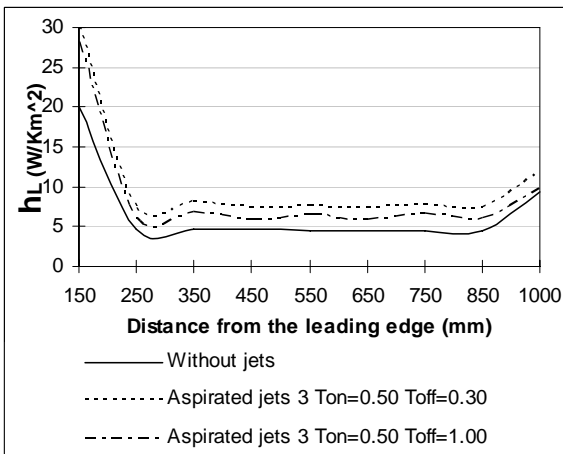


Figure 10: Local convection coefficient vs. distance from the leading edge for different aspirated jets activity times, with $\Delta T=40K$.

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 the 3rd on the aluminum wall. This configuration is indicated in the tests as 3 (Figure 9).

The activity and inactivity times of the jets to maximize h have been, respectively, $T_{on}=0.50s$ and $T_{off}=0.30s$: this is not the same time combination relative to the expired jets (Figure 10). The comparison between the local heat transfer coefficient with expired and aspirated jets shows that the first ones are less efficient at $\Delta T=40K$ (Figure 11).

Expired jets with $\Delta T=70K$

In these experimental tests we verified that the optimal velocity was the same as for previous temperature drops

(Figure 12). Also, 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 (Figure 13).

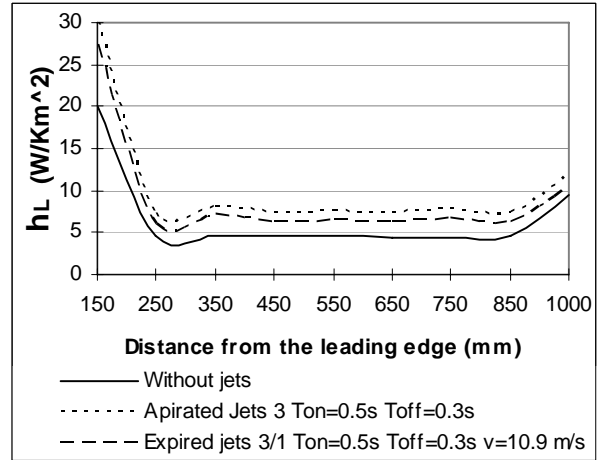


Figure 11: Comparison between local convection coefficient vs. distance from the leading edge for the best configuration with expired, aspirated, and without jets with $\Delta T=40K$.

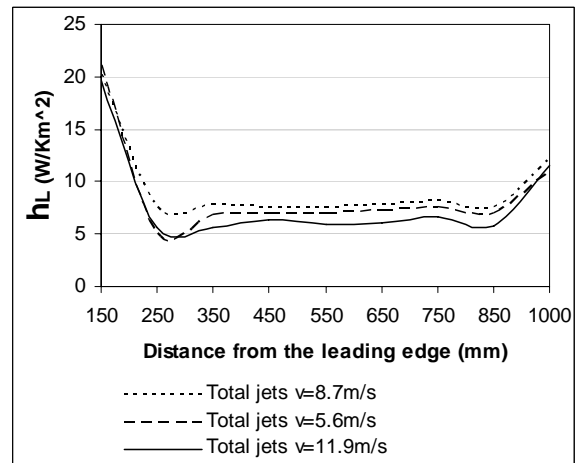


Figure 12: Local convection coefficient vs. distance from the leading edge for different active expired jets velocity, with $\Delta T=70K$.

The activity and inactivity times of the jets maximizing the heat transfer coefficient have been, respectively, $T_{on}=0.25s$ and $T_{off}=0.25s$ (Figure 14).

In short, the average increase of h between the configurations with and without jets (optimum configuration) was less than 10%.

Therefore, the presence of pulsating jets with great temperature differences is not useful for the enhancement of heat transfer, because the increase of h is lower than the experimental error (13.5%).

The transition from the laminar to the turbulent condition occurs at 640mm from the leading edge, according with the theoretical result.

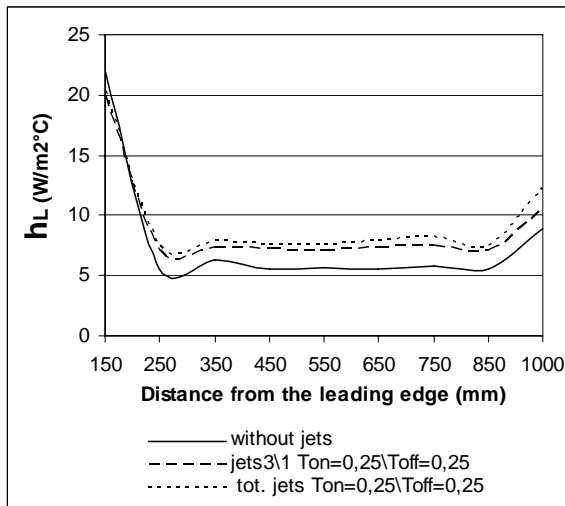


Figure 13: Local convection coefficient vs. distance from the leading edge for different configurations of active expired jets, with $\Delta T=70K$.

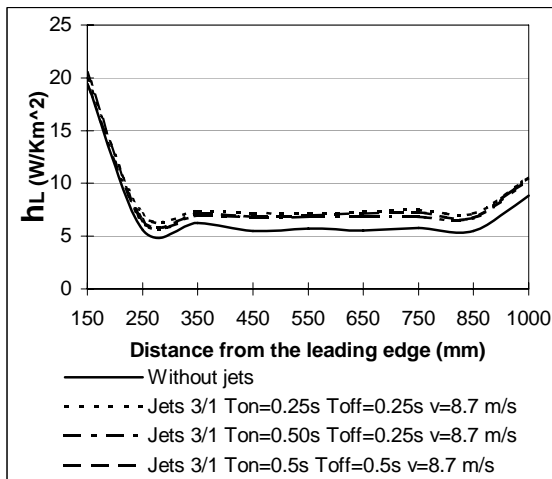


Figure 14: Local convection coefficient vs. distance from the leading edge for different expired jets activity and inactivity times, with $v=8.7m/s$ and $\Delta T=70K$

Aspirated jets with $\Delta T=70K$

The first tests have been performed with the 3rd active jets array on the lexan wall too (Figure 15), but the comparison between Figures 15 and 16 shows that the heat transfer coefficient difference is unimportant: so, with aspirated jets, we did not used jets on the lexan wall. The active jets array maximizing h is the first one from the bottom (Figure 16).

The activity and inactivity times of the jets to maximize h have been, respectively, $T_{on}=0.25s$ and $T_{off}=0.25s$ (Figure 17): this is the same time combination relative to the expired jets (compare Figures 17 and 14).

The comparison between the local heat transfer coefficient with expired and aspirated jets shows that the first ones are more efficient at $\Delta T=70K$ (Figure 18).

The experimental tests have shown that the aspirated pulsating jets are more efficient than the continuous ones: in particular, in the most favorable conditions, the heat transfer coefficient is $8.5W/m^2K$ and it increases more than 48% with respect to the case without jets ($5.7W/m^2K$).

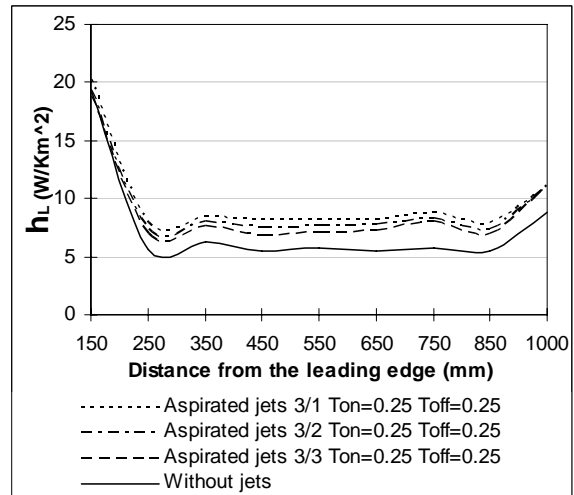


Figure 15: Local convection coefficient vs. distance from the leading edge for different configurations of active aspirated jets, with $\Delta T=70K$.

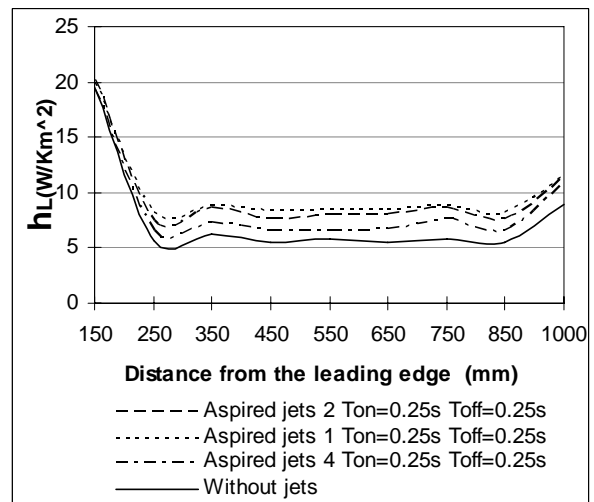


Figure 16: Local convection coefficient vs. distance from the leading edge for different configurations of active aspirated jets, with $\Delta T=70K$.

It can be observed that, both in the presence and in the absence of aspirated and expired jets, the qualitative free convection coefficient behavior shows a clear initial decrease, then a range with an almost constant h is present.

Finally, the transition between laminar and turbulent convection happens at 690mm from the leading edge and, after that point, the heat transfer coefficient increases.

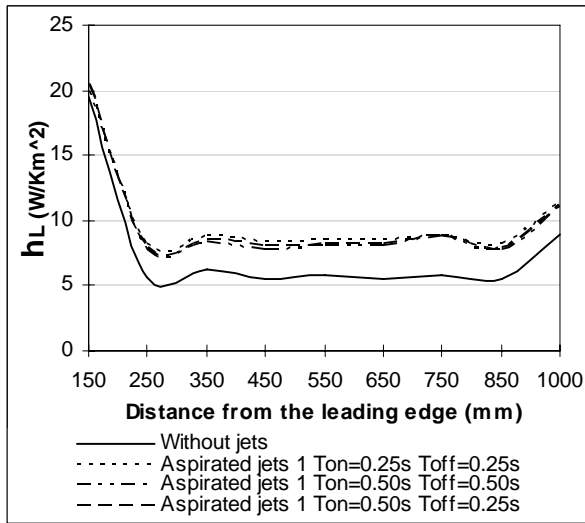


Figure 17: Local convection coefficient vs. distance from the leading edge for different times of aspirated jets, with $\Delta T=70K$.

ANALYSIS OF FREE CONVECTION RESULTS

For expired jets it was found that the heat transfer was maximized for the following parameters:

- the air jets exit velocity was equal to 8.5m/s in all the tests performed;
- the times of jets activity and inactivity decreased with increasing ΔT ;
- the two horizontal lines maximizing the heat transfer convection coefficient were, starting from below, the first on the aluminum wall and the last on the lexan wall (except for the configuration with all active jets);
- then the h increase in the presence of expired jets decreases monotonically with ΔT passing from 84% for $\Delta T=25K$ to 27% for $\Delta T=70K$.

On the contrary, the aspirated jets are very effective with an intermediate ΔT (with a temperature drop of 40K, the increase gets to 67% in comparison with the case without jets).

In fact his air exit velocity determine a square Reynolds number equal to Grashof number. A qualitative analysis of the air velocity field was performed by means of a hot wire anemometer. Table 1 shows briefly the global free convection coefficients without jets with temperature drops of 25, 40, and 70K and the corresponding values for the best configurations of the expired and aspirated jets.

Finally, the experimental correlations proposed by McAdams [19] and Churchill-Chu [20] for the Nusselt number in cases without jets were not acceptable with high ΔT between wall and air (in our case with $\Delta T=70K$).

Actually, the tests of the above-mentioned researchers were performed with a temperature drop of 20K; the presence of pulsating jets did not change the transition distance between laminar and turbulent conditions, corresponding to $Ra=10^9$ in all cases.

The jets only induced a local destabilization of the boundary layer.

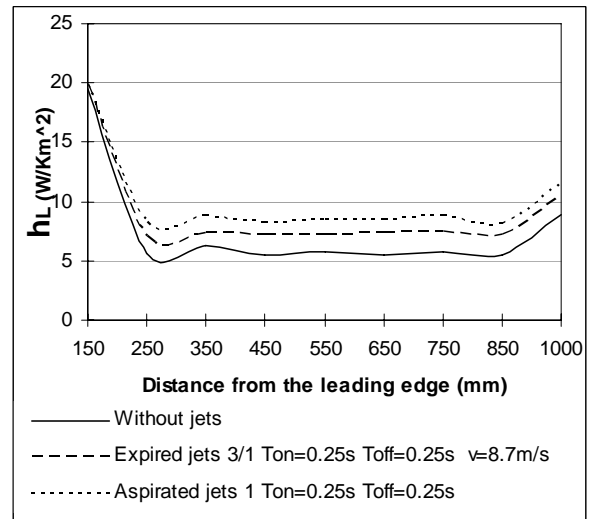


Figure 18: Comparison between local convection coefficient vs. distance from the leading edge for the best configuration with expired, aspirated, and without jets, with $\Delta T=70K$.

Table 1: Free convection coefficient vs. ΔT for expired, aspirated and without jets.

	h without jets $W/m^2 K$	h expired jets $W/m^2 K$	h aspirated jets $W/m^2 K$
$\Delta T=25K$	3.9	7.1 (+84%) jets 3/1 $T_{on}/T_{off}=1.25/0.75$	6.1 (+57%) jets 2 $T_{on}/T_{off}=1.25/0.75$
$\Delta T=40K$	4.5	6.4(+41%) jets 3/1 $T_{on}/T_{off}=0.50/0.50$	7.6 (+67%) jets 3 $T_{on}/T_{off}=0.50/0.30$
$\Delta T=70K$	5.7	7.3 (+27%) jets 3/1 $T_{on}/T_{off}=0.25/0.25$	8.5 (+48%) jets 1 $T_{on}/T_{off}=0.25/0.25$

MIXED CONVECTION EXPERIMENTAL RESULTS

The heat transfer coefficient about aspirated jets tests in mixed convection don't show enhancement in comparison with case without jets: so we have performed only tests with expired jets.

All the tests have demonstrated that the continuous jets are more efficient than the pulsated ones: in particular, in the most favorable conditions ($\Delta T=25K$), the heat transfer coefficient increases more than 37%.

Expired jets with $\Delta T=25K$

With a wall temperature of 323K, the fan velocity must be equal to 0.7m/s to determine the mixed convection conditions ($Gr \approx Re^2$): then before each test with a wire anemometer this value has been controlled.

Without jets the average convection coefficient is $7.1 \text{ W/m}^2\text{K}$. In this case the activity and inactivity times of the jets are resulted completely un-influential: in fact the continuous jets have given the best results (Figure 19).

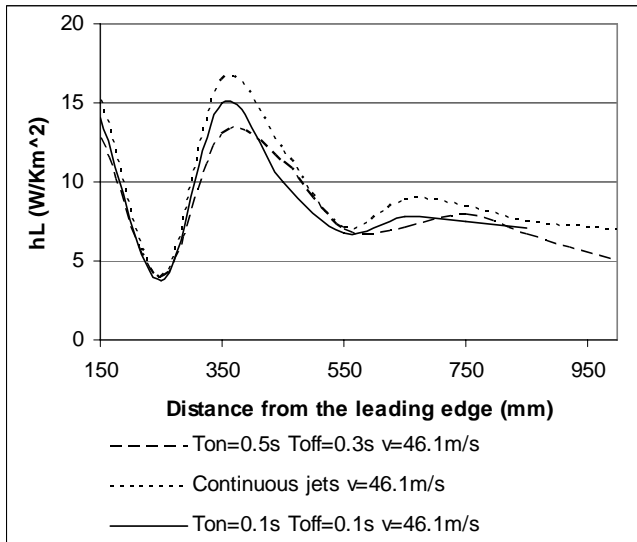


Figure 19: Local convection coefficient vs. distance from the leading edge for different activity and inactivity times of the jets, with 4th line of horizontal jets and with $\Delta T=25\text{K}$

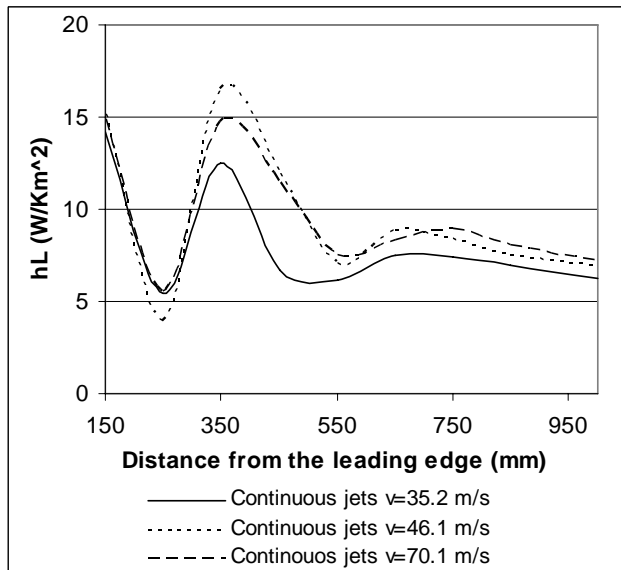


Figure 20: Local convection coefficient vs. distance from the leading edge for different jets velocity, with 4th line of horizontal jets and with $\Delta T=25\text{K}$

In the presence of continuous jets the tests have shown that h increases with the velocity until $v=46.1 \text{ m/s}$ than it decrease (Figure 20): indeed in the best conditions at 15.3 m/s , Δh is equal to +17%; at 23.5 m/s , $\Delta h=+19\%$; at 46.1 m/s , $\Delta h=+37\%$; at 70.1 m/s , $\Delta h=+33\%$.

With the optimal velocity, the horizontal line of most effective jets, except for the totality of them, have been the 4th on the aluminum wall; this configuration is indicated in the paper as Jets 4 (Figure 21).

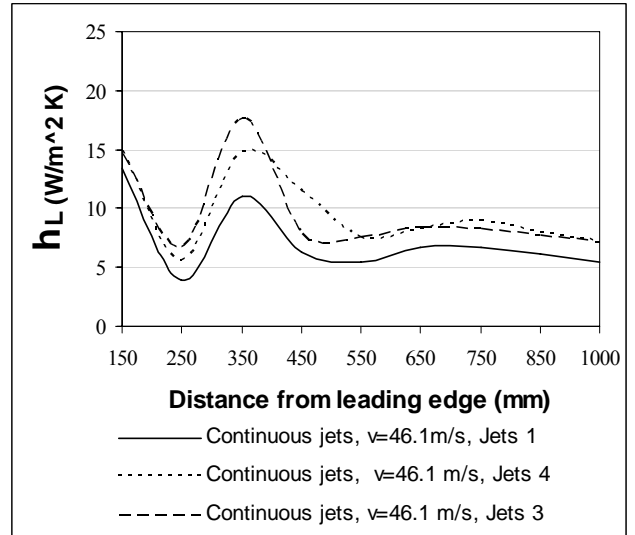


Figure 21: Local convection coefficient vs. distance from the leading edge for different active expired jets configurations, with $v=46.1 \text{ m/s}$ and $\Delta T=25\text{K}$

Expired jets with $\Delta T=40\text{K}$

With a wall temperature of 338K , the fan velocity must be equal to 0.9 m/s to determine the mixed convection conditions ($Gr \approx Re^2$): then before each test this value has been checked by a hot wire anemometer.

Without jets the average convection coefficient is $8.9 \text{ W/m}^2\text{K}$.

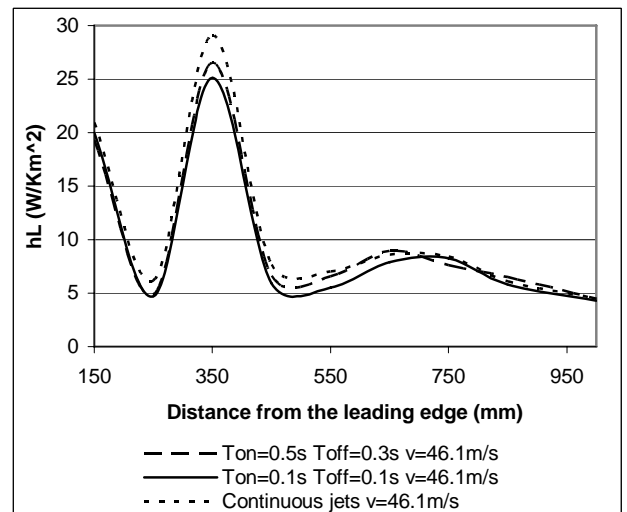


Figure 22: Local convection coefficient vs. distance from the leading edge for different activity and inactivity times of the jets, with 4th line of horizontal jets and with $\Delta T=40\text{K}$

In this case, too, the activity and inactivity times of the jets are resulted completely un-influential: in fact the continuous jets have given the best results (Figure 22).

In the presence of continuous jets and in the optimal conditions, the tests have shown that h increases with the velocity until $v=46.1\text{m/s}$ than it remain constant (Figure23): indeed in the best conditions at 15.3 m/s , Δh is equal to $+3\%$; at 23.5m/s , $\Delta h=+10\%$; at 46.1m/s , $\Delta h=+24\%$; at 70.1m/s , $\Delta h=+24\%$.

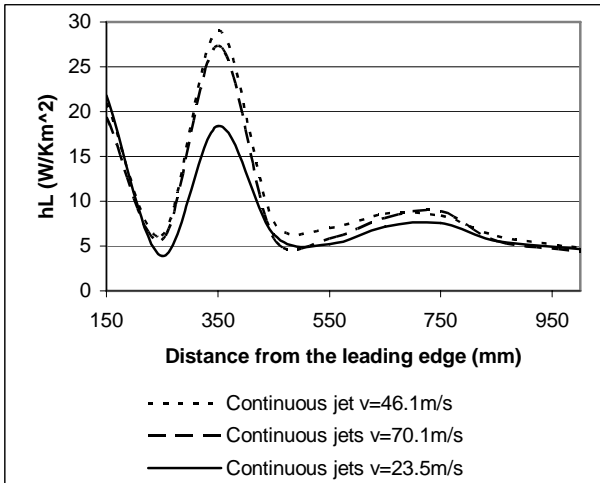


Figure 23: Local convection coefficient vs. distance from the leading edge for different jets velocity, with 4th line of horizontal jets and with $\Delta T=40\text{K}$

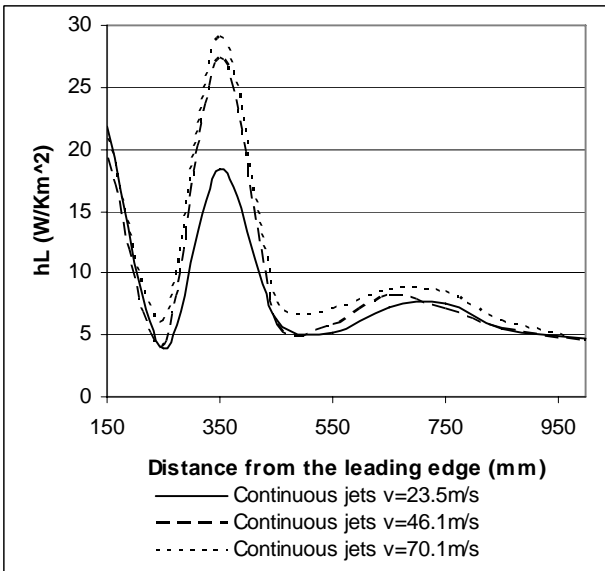


Figure 24: Local convection coefficient vs. distance from the leading edge for different jets velocity, with 3rd line of horizontal jets and with $\Delta T=40\text{K}$

With the jets velocity equal to 46.1m/s , the horizontal line of most effective jets, except for the totality of them, have been the 4th from below on the aluminum wall; instead with

$v=70.1\text{m/s}$, the horizontal line of most effective jets, have been the 3rd on the aluminum wall (Figure 24).

Expired jets with $\Delta T=70\text{K}$

In this case, with a wall temperature of 368K , the fan velocity is equal to 1.2m/s to determine the mixed convection conditions ($Gr \approx Re^2$). Without jets the average convection coefficient is $12.2\text{W/m}^2\text{K}$.

Also in this case the activity and inactivity times of the jets are resulted completely un-influential: in fact the continuous jets have given the best results (Figure 25).

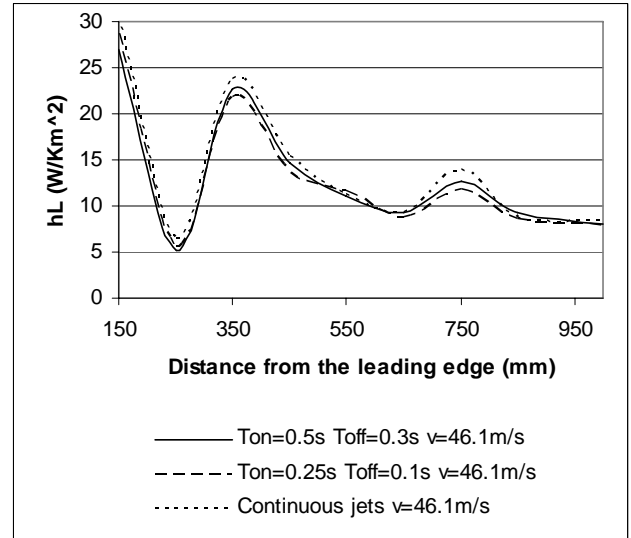


Figure 25: Local convection coefficient vs. distance from the leading edge for different activity and inactivity times of the jets, with 4th line of horizontal jets and with $\Delta T=70\text{K}$

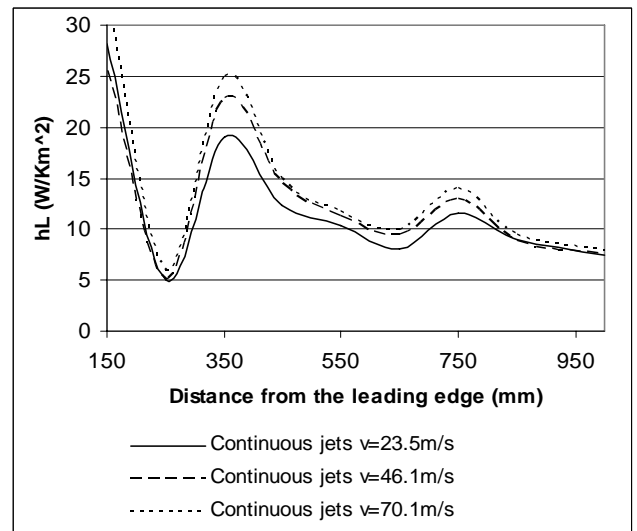


Figure 26: Local convection coefficient vs. distance from the leading edge for different jets velocity, with the 4th line of horizontal jets and with $\Delta T=70\text{K}$

The local heat transfer coefficient increases monotonically with the exit jets velocity, (Figure 26): indeed in the best conditions at 15.3 m/s, Δh is equal to +5%; at 23.5m/s, $\Delta h=+8\%$; at 46.1m/s, $\Delta h=+12\%$; at 70.1m/s $\Delta h=+15\%$. The horizontal line of most effective jets, except for the totality of them, have been the 4th on the aluminum wall (Figure 27).

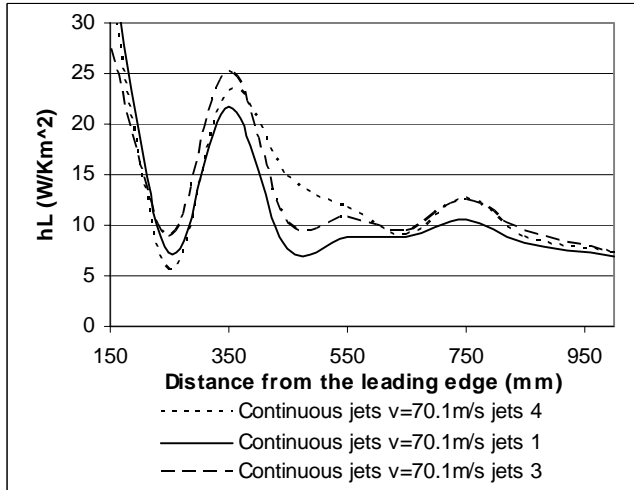


Figure 27: Local convection coefficient vs. distance from the leading edge for different active expired jets configurations, with $v=70.1\text{m/s}$ and $\Delta T=70\text{K}$

ANALYSIS OF MIXED CONVECTION RESULTS

Table 2 shows briefly the average mixed convection coefficients without jets with temperature drops of 25, 40, and 70K and the corresponding values for the best configurations of the expired jets.

Table 2: Mixed convection coefficient vs. ΔT

	h without-jets $\text{W/m}^2\text{K}$	h continuous expired jets $\text{W/m}^2\text{K}$
$\Delta T=25\text{K}$	7.1	9.7 (+37%) Jets 4 $v=46.1\text{m/s}$
$\Delta T=40\text{K}$	8.9	11.1(+24%) Jets 3 $v=70.1\text{m/s}$ Jets 4 $v=46.1\text{m/s}$
$\Delta T=70\text{K}$	12.2	14.0(+15%) Jets 4 $v=70.1\text{m/s}$

We can observe that:

- the use of pulsated jet is useless: in fact the continuous jets maximize the average heat transfer coefficient in any case (ΔT);
- the percent increase of h decreases monotonically with ΔT ;
- for high ΔT (over 70K) the increase of h is comparable with the experimental error and then the use of jets is not useful;

- the local heat transfer has a absolute maximum near the leading edge and a relative maximum in the neighborhood of the jets, in other terms in the zone of the perturbation;
- in the case without jets the founded peak comes back in the experimental error.

CONCLUSION

From the comparison of the experimental data in mixed and free convection we can affirm:

- both in free and mixed convection the presence of expired jets establishes a heat transfer enhancement that decreases when ΔT increases;
- for consideration of energy saving, the optimal configuration of active jets is the 1st from below on the aluminum wall in free convection and the third or the 4th in mixed convection; besides in the first case a line of jets on the lexan wall is necessary to destabilize the dynamic field;
- in free convection the pulsated jets are more efficient than the continuous ones; the contrary occurs in mixed convection;
- the jets velocity that maximize h is about 9 m/s in free convection 46 or 70 m/s in mixed convection: that great difference can be caused by different dynamic fields characterized respectively by low or high kinetic energy flux;
- for high temperature drop ($\Delta T \geq 70\text{K}$) between vertical wall and air the use of jets is useful for free convection only;

Finally correlations about free and mixed convection with pulsated or continuous jets are not available: in any case the author is studying this problem.

REFERENCES

- [1] Pohlhausen, E., 2. *Anges. Meth. Mech.* 1, 1921, pp.1151-1160.
- [2] Ostrach, S., An Analysis of Laminar Free-Convection Flow and Heat Transfer about a Flat plate Parallel to the Direction of the Generating Body Force, *NACA TN*, 1952, pp. 2653-2661.
- [3] Eckert, E.R.G., *Heat Mass Transfer*, 1959, pp. 311-321.
- [4] Zografos, A.I., Sunderland, J.E., Natural Convection from Pin Fin Array, *Experimental Thermal and Fluid Science*, Vol. 3, 1990, pp. 440-450.
- [5] Tanda, G., Natural Convection Heat Transfer from a Staggered Vertical Plate Array, *ASME Journal of Heat Transfer*, Vol. 115, 1993, pp. 938-946.
- [6] Aziz, A., Lunardini, V.J., Multidimensional Steady Conduction in Convecting, Radiating and Convecting - Radiating Fins and Fin Assemblies, *Heat Transfer Engineering*, Vol. 16, n. 3, 1995, pp. 32-44.
- [7] Ruckenstein, E., On the Laminar and Turbulent Free Convection Heat Transfer from a Vertical Plate Over the Entire Range of Prandtl Numbers, *International Comm. In Heat and Mass Transfer*, Vol. 25, 1998, pp. 1009-1018.
- [8] Bejan, A., Cunnington, G.R., Theoretical Considerations of Transition to Turbulence in Natural Convection near a Vertical Wall, *Int. Journal of Heat and Fluid Flow*, 1983, pp. 131-140.
- [9] Schlichting, H., *Boundary Layer Theory*, New York, McGraw-Hill Ed., 7th edition 1987.

- [10] Bell, C.M., Ligrani, P.M., Hull, W.A., Norton, C.M., Film cooling subject to bulk flow pulsations: effects of blowing ratio, freestream velocity and pulsation frequency, *International Journal of Heat and Mass Transfer*, Vol. 42, 1999, pp. 4333-4344.
- [11] Ligrani, P.M., Gong, R., Cuthrell, J.M., Lee, J.S., Effects of bulk flow pulsations on film-cooled boundary layer structure, *Transactions of the ASME*, Vol.119, 1997, pp. 323-333.
- [12] Seo, H.J., Lee, J.S., Ligrani, P.M., Effects of bulk flow pulsations on film cooling from different length injection holes at different blowing ratios, *Transaction of the ASME*, Vol.121, 1999, pp. 127-137.
- [13] Ali, M.E., On thermal boundary layer on a power-law stretched surface with suction or injection, *International Journal of Heat and Fluid Flow*, Vol.19, 1995, pp. 280-290.
- [14] Bartoli, C., Heat transfer enhancement between a vertical wall and air with pulsating jets. *Proceedings of 4th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics*, Cairo, Egypt, 18-24 September 2005, pp. BC3, 1-5.
- [15] Bartoli, C., Heat transfer enhancement between a vertical wall and air with pulsating jets, *Proceedings of Asme-Ati Conference "Energy: production, distribution and conservation"* Milan, May 14-17th 2006, pp. 813-822.
- [16] Bartoli, C., Heat transfer enhancement between a vertical wall and air with pulsating aspirated and expired jets, *Proceedings of the 3rd BSME-ASME International Conference on Thermal Engineering* 20-22 December, 2006, Dhaka, Bangladesh, BA150 pp.1-6
- [17] Bartoli, C., Heat transfer enhancement between a vertical wall and air with pulsating aspirated and expired jets, *Accepted by International Journal of Heat and Technology*.
- [18] Moffat, R.J., Describing the uncertainties in experimental results, *Exp. Fluid and Thermal Science*, Vol. 1, 1998, pp. 3-29.
- [19] McAdams, W.M., *Heat Transmission*, New York, McGraw-Hill, 1954.
- [20] Churchill, S. W., Chu, H. S., Correlating Equations for laminar and Turbulent Free Convection from a Vertical Plate, *Int. J. Heat Mass Transfer*, Vol. 18, 1975, pp. 1323-1329.