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ATTACHMENT OF A COLD PLANE JET TO THE CEILING - LENGTH OF RECIRCULATION REGION AND SEPARATION DISTANCE

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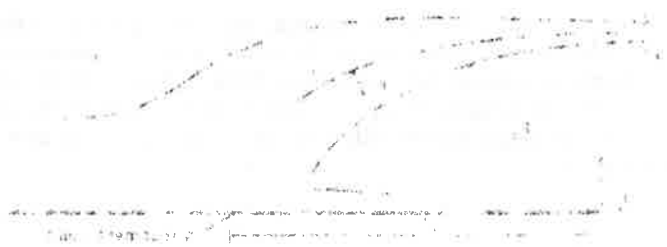
SUMMARY

The experiments were arranged such that a *two-dimensional jet* was supplied above a plate. The distance between the plate and the supply point could be varied continuously.

Due to the proximity to the surface a pressure difference is created that curves the jet towards the surface.

In the first part of the paper are reported results from measurements of the length of the recirculation region at isothermal supply of air. The length of the recirculation region was determined by recording the static pressure distribution along the plate.

In the second part the effect of an opposing buoyancy force is explored and reported. This force was created by heating the jet which, from a physical point of view, is the same as supplying cold air below a ceiling. If the buoyancy force becomes sufficiently strong the jet will separate from the surface. In this part of the paper the distance to the separation point and the effect of the buoyancy forces upon the recirculation region is reported.



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INTRODUCTION

When supplying air with high velocity to a room the flow is directed along the room surfaces. The supply point is often located close to the ceiling. The proximity of the surface restricts entrainment of ambient air to that side which causes a pressure difference ("Coanda" effect) that curves the jet towards to the nearest surface, see Fig. 1. At the point of attachment the jet is divided into two parts, one of which is fed back into the recirculation region while the other continues as a wall jet.

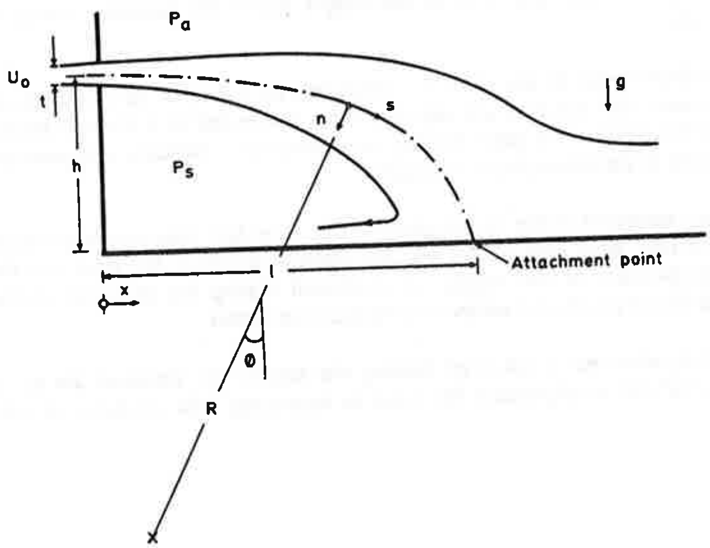


Fig. 1. Jet that is curved towards a surface

A supply of cold air with the ventilation system is often used as a method for controlling the room air temperature. In recent years the supply of air at extremely low temperatures (~+5°C) has come into use [1].

With increasing distance from the supply the buoyancy force increases. If the buoyancy force becomes sufficiently strong the jet will separate from the surface. The location of this *point of separation* is important to predict. If e.g. cold air is supplied and the separation from the ceiling occurs well before the jet has reached the opposing wall then the cold jet will be dumped into the occupied zone where it may cause unacceptable thermal discomfort. The importance of the subject has attracted the attention of many researchers within ventilation engineering, [2], [3].

EXPERIMENTAL ARRANGEMENT

The apparatus consisted of a horizontal baseplate, two vertical sidewalls and a vertical end wall. In the end wall the supply device was located which consisted of a rectangular opening of thickness $t = 0.02$ m and width 0.2 m spanning the whole width of the channel. Before issuing from the slot the air passed several fine-mesh nets. Velocity measurement along the width of the slot showed a maximum deviation of ± 3 % from the mean velocity value.

The vertical side walls were fixed to the baseplate with a distance of separation equal to 0.2 m. The vertical endplate could slide vertically along channels in both side walls. By this arrangement the height, h, of the supply above the baseplate could be changed continuously.

The static pressure distribution on the plate was measured by means of surface pressure tappings. Via a scannervalve the pressure tappings were connected to a Furness micro-meter. The time of integration for each reading amounted to 5 minutes. All pressure readings were referred to the atmospheric pressure.

By a duct a fan was connected to the supply device. The flow rate was measured by an orifice plate. Due to heat generated by the fan and friction losses in the duct and the orifice plate the temperature of the supply air increased during the transport in the duct. This made it difficult to achieve perfect isothermal conditions.

The effect of the buoyancy was studied by heating the supply air. Because the air is supplied *above* a plate this is physically the same as supplying cold air *below* a ceiling.

LENGTH OF RECIRCULATION REGION

Theory

When a streamline is curved a pressure drop exists across the streamline in the direction of the centre of curvature. According to Bernoulli's law this pressure drop $\partial p/\partial n$ amounts to:

$$\frac{U^2}{R} = -\frac{1}{\rho}\frac{\partial p}{\partial n} - g\frac{\Delta\rho}{\rho}\cos\phi \qquad (1)$$

where U is the velocity, ρ is the density, R is the radius of curvature and n is normal to the streamline in the plane of the radius of curvature. The positive direction of the normal is directed towards the center of curvature. The angle ϕ is the acute angle between the normal and the vertical.

At isothermal conditions ($\Delta\rho = 0$), integration of this relation gives the following relationship between the pressure difference, Δp, momentum per unit span, M, and radius of curvature, R,

$$\Delta p(s) = \frac{M(s)}{R(s)} \qquad (2)$$

where $\Delta p = (p_a - p_s)$ and s measures distance from the supply along the trajectory of the jet.

Due to the non-uniform pressure field we shall not expect the momentum to be conserved.

When the flow is affected by a buoyancy force the above relationship is cast into

$$\Delta p(s) = \frac{M(s)(1 - \cos\phi\, Ar(s))}{R(s)} \qquad (3)$$

where Ar(s) is the local Archimedes number.

$$Ar(s) = \frac{g\frac{\Delta T}{T}b(s)}{U(s)^2} \qquad (4)$$

where b(s) is the total thickness of the jet.

If we as an approximation set the momentum equal to the initial momentum per unit width, $\rho U_0^2 t$, the above relationship becomes:

$$\Delta p(s) = \frac{\rho U_0^2 t(1 - \cos\phi\, Ar(s))}{R(s)} \qquad (5)$$

In case there is no loss of heat and momentum, then for a two-dimensional jet the following relation holds between the local Archimedes number, Ar(s), and the supply Archimedes number, Ar(0):

$$Ar(s) = K Ar(0)\left(\frac{s}{t}\right)^{3/2} \qquad (6)$$

According to the above relation the local Archimedes number increases with increasing distance from the supply which means that the buoyancy becomes relatively more important.

The above derivation of the pressure difference between the ambient and the recirculation region is based on a number of simplifying assumptions. Starting from the above expression it is natural to assume the following relationship:

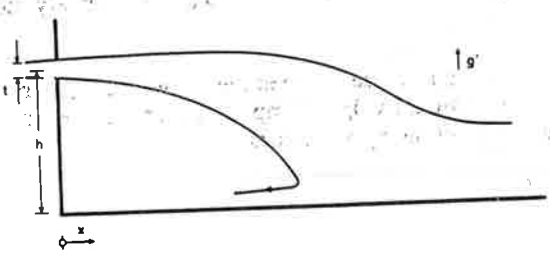
$$\frac{\Delta p(s)}{U_0^2} = \frac{t}{h}(1 - KAr(0)^n) \qquad (7)$$

where the constant K and the exponent n have to be determined experimentally.

Isothermal conditions - supply at a fixed height above the plate but at different velocities

The static pressure readings along the base plate are shown in Fig. 2. The pressure readings show the expected behaviour. Within the recirculation region there is an underpressure and when one proceeds along the plate the pressure increases and becomes greater than the ambient pressure when the jet impinges upon the plate. The location of the attachment point is defined as the point where the maximum pressure occurs. Further downstream the pressure decreases and approaches zero.

According to the dimensional analysis carried out by Sawyer [4] the length of the recirculation region is, at sufficiently high Reynolds numbers, independent of the Reynolds number. This is verified by our measurements. When nondimensionalized by the supply velocity squared the pressure readings collapse on almost the same curve. (In Fig. 5 is shown the recorded pressure.)



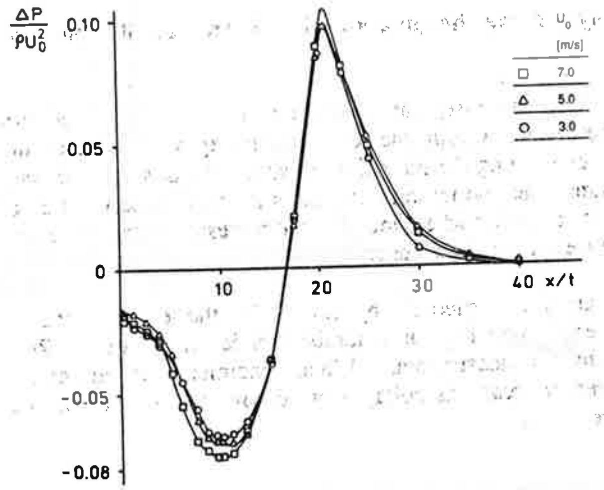
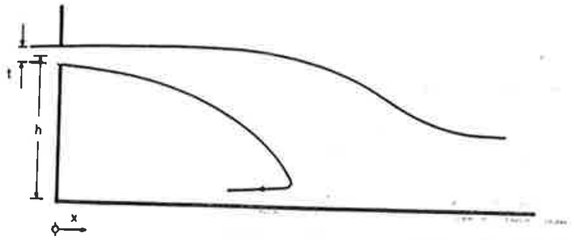


Fig. 2. Static pressure distribution along the plate. Isothermal conditions. Clearance h = 250 mm (h/t = 12.5)

Isothermal conditions - supply at varying heights and velocities

The experiments were carried out with a fixed velocity equal to 7 m/s and the clearance varying between 50 to 250 mm. Figure 3 shows the pressure distribution along the plate.



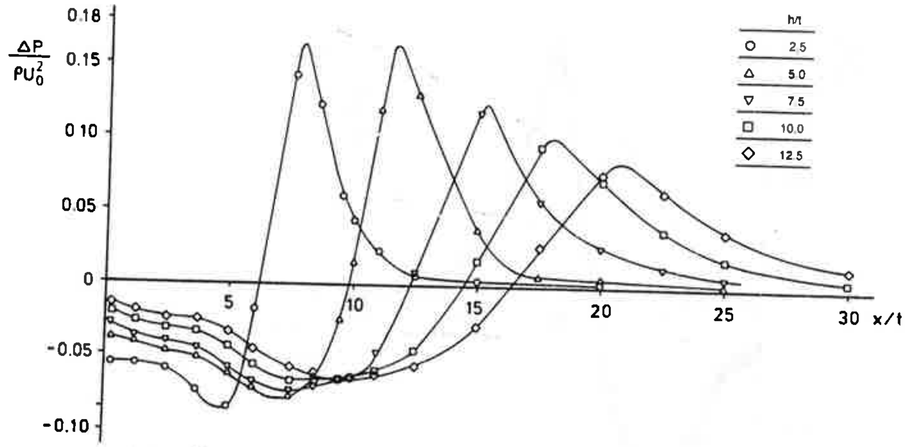
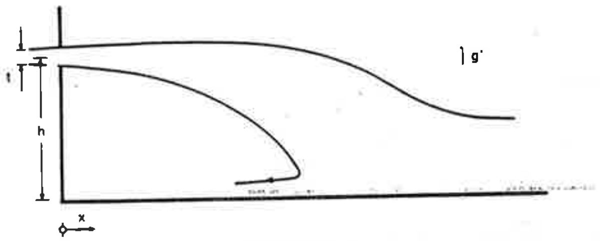


Fig. 3. Static pressure distribution along the plate. Isothermal conditions. Different heights above the plate

Figure 4 shows both the location, X_{max}, of the maximum pressure (length of the recirculation region) and the location of the minimum pressure, X_{min}, as a function of of the clearance h.



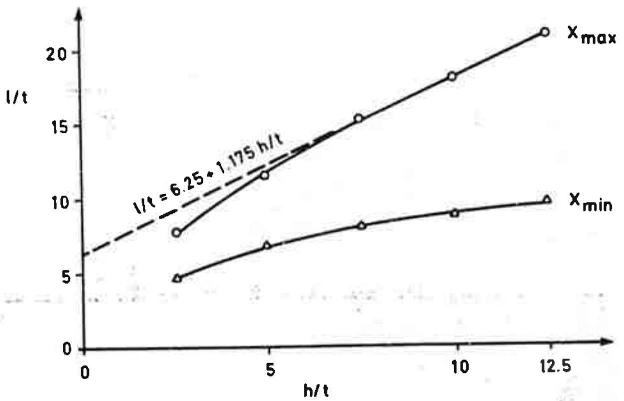


Fig. 4. Effect of height above surface on the attachment distance and the location of the minimum pressure

Between 5 < h/t < 13 the recorded length of the recirculation region follows the following relation

$$\frac{l}{t} = 6.25 + 1.175\frac{h}{t}$$

Non-isothermal conditions - supply at a fixed height above the plate but with different discharge Archimedes numbers

In all these experiments the clearance and supply velocities were the same as in Fig. 2. The supply air was heated giving an upward acting effective gravity $g' = g\Delta\rho/\rho$. The Archimedes numbers and the temperature difference, ΔT, between the supply and the ambient are shown in Fig. 5.

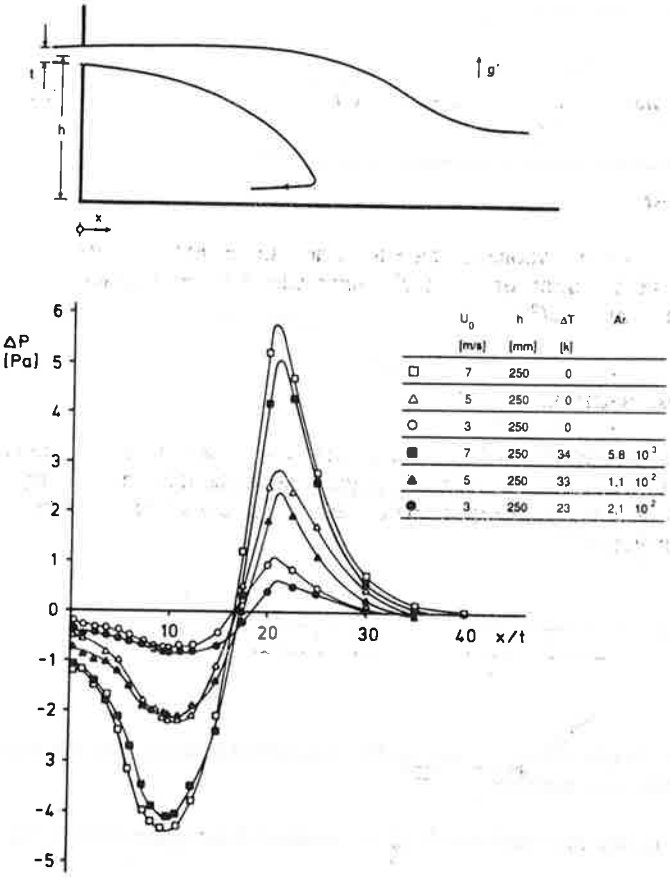


Fig. 5. **The effect of opposing buoyancy force (heating the jet). Clearance h = 250 mm (h/t = 12.5)**

The opposing buoyancy force lowers the pressure difference both in the recirculation region and where the jet impinges upon the plate except for the case of U_o = 3 m/s, wher the buoyancy effect is "reversed" in the recirculation region. However, the location of the maximum pressure (attachment point) and the minimum pressure are unaltered.

DISTANCE TO POINT OF SEPARATION

Theory

Several researchers have found that the separation distance, X_s, is proportional to the discharge Archimedes number Ar(0):

$$\frac{X_s}{t} = K Ar(0)^n \qquad (8)$$

where the constant K and the exponent n have to be determined experimentally.
If we assume that the evolution of the local Archimedes number follows relation (6) then the exponent n becomes 2/3.

Supply located flush to the plate

The separation distance was obtained by adding smoke and observing the location of the point where the jet lifted from the plate. This point could be determined within ± 5 cm. Figure 6 shows the recorded separation distance, X_s, as a function of the supply Archimedes number Ar(0).

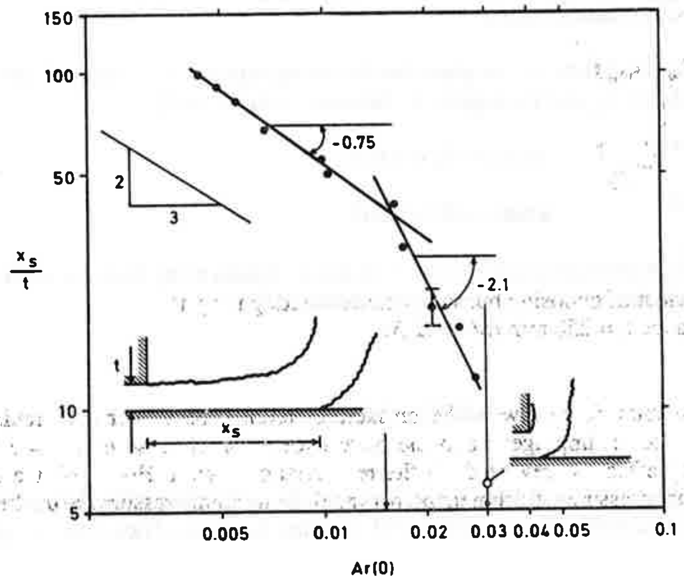


Fig. 6. Separation distance as a function of the supply Archimedes number Ar(0)

In Fig. 6 two distinct branches appears. At Archimedes numbers less than 0.015 the exponent n (slope in Fig. 6) is -0.75 whereas at larger Archimedes number the exponent becomes -2.1. The first slope is close to the theoretical one (relation 6) and occurs when the separation occurs far from the supply ($X_s/t > 40$) whereas the latter slope occurs closer to the supply.

When the Archimedes number is just below 0.03 the jet breaks away from the surface as soon as it leaves the nozzle.

Supply located at various heights

The data obtained from these experiments show a large scatter. The only general conclusion that can be made is that at a fixed Archimedes number, the separation distance increases with increasing clearance h.

CONCLUSIONS

The experiments confirm that the length of the recirculation region is not affected by the supply velocity.

Introducing an opposing buoyancy force by e.g. cooling a ceiling jet does not affect the length of the recirculation region.

With the supply located flush to the plate the following relation was obtained between the separation distance X_s and the supply Archimedes number Ar(0):

$X_s \sim Ar(0)^{-0.75}$ when $Ar(0) < 0.015$

$X_s \sim Ar(0)^{-2.1}$ when $Ar(0) > 0.015$

The critical supply Archimedes number at which the jet breaks away from the surface as soon as it leaves the nozzle was found to lie just below 0.03.

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