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#### MEASUREMENTS ON BUOYANT JET FLOWS FROM A CEILING-MOUNTED SLOT DIFFUSER

Summary. Bouyant jet will often take place as part of the air distribution in air conditioned rooms. The thickness of a cold wall jet increases with the heat load, and the jet may further separate from the ceiling at some distance from the diffuser and flow into the occupied zone.

The paper will show the influence of the Archimedes number and the Reynolds number in relevant conditions for practical air conditions. The measurements will show the buoyancy effect on velocity distribution and temperature distribution in the wall jet from a ceiling - mounted slot diffuser which is important information when the wall jet is used as boundary condition in a numerical prediction procedure. The measurements will also show the penetration depths obtained with a wall jet following the ceiling in a room. The penetration depth for this type of diffuser will be compared with penetration depth for other types of grilles and diffusers.

#### INTRODUCTION

Ceiling-mounted slot diffusers in ventilated rooms will often generate a flow of the wall jet type. The jet follows the ceiling, entrains air from the occupied zone and generates a re-circulating flow in the whole room.

This paper will deal with the flow in the ceiling region. The wall jet flow is especially influenced by diffuser design and surrounding details such as distance to the ceiling and the ceiling structure. The flow is less influenced by other parameters in the room such as length, width, height and furnishings.

It is important to study the conditions and locations where the flow can be described as a wall jet. This description is useful when different diffusers are compared, and it is the background for calculation of "throw" and "penetration depth", see (1). It is also convenient to use the wall jet description of inlet conditions in computer predicted flow in rooms. This description makes it possible to ignore details at the diffuser as e.g. vanes resulting in reduction of computer storage and increased computation speed, see ref. (2).



Fig. 1. Ceiling-mounted slot diffuser with small width.

Rys. 1. Sufitowy nawiewnik szczelinowy o małej szerokości

#### DIFFUSER

Fig. 1 shows one of the diffusers used for the measurements in the paper. The diffuser has four adjustable openings, and it is possible to direct the flow either in two horizontal directions or vertically downwards. The experiments in this paper describe situations where all the flow is in the same horizontal direction, or situations where the flow is divided in two horizontal directions. The main part of this paper describes the last mentioned situation.

The present paper will deal with the two-dimensional flow from a slot diffuser and also the transition to three-dimensional flow in case of a slot diffuser with small width. The experiments are therefore made with two slot diffusers of the same type, but with different widths

SLA 4 - 60 width: 0.60 m

SLA 4 - 180 width: 1.80 m

#### WALL JET FLOW

A two-dimensional wall jet flow is a flow established close to a surface where air is supplied parallel to the surface from a slot with a large width. The wall jet conditions are fulfilled when the velocity profiles can be expressed in a single universal profile normalized with a local length and a local velocity and when growth rate and velocity decay can be expressed by the following equations, see Rajaratnam (3) and Schwarz and Cosart (4).

$$\frac{\delta}{h} = D_p \frac{x+x_0}{h} \quad (1)$$

$$\frac{u}{u_0} = K_p \sqrt{\frac{h}{x+x_0}} \quad (2)$$

$\delta$  is the wall jet thickness perpendicular to the surface at the velocity  $u/2$ , where  $u$  is the local maximum velocity.  $x$  is the length from the opening and  $h$  is the slot height.  $x_0$  is the virtual origin of the wall jet growth and velocity decay, while  $D_p$  and  $K_p$  are constants and  $u_0$  is the supply velocity.

$x_0$  is small compared to the distance  $x$  in the wall jet, and equation (1) shows that the growth of the wall jet thickness is in practice proportional to the distance from the opening with the growth rate  $D_p$ . Equation (2) shows that the velocity ratio  $u_x/u_0$  is proportional to  $1/\sqrt{x}$ , which is typical of a two-dimensional wall jet, and it expresses that the momentum flow is preserved in the jet.

A thermal two-dimensional wall jet can be derived from equations (1) and (2), and from the following equation for the temperature distribution

$$\frac{T_x - T_R}{T_0 - T_R} = K_{PT} \sqrt{\frac{h}{x + x_0}} \quad (3)$$

where  $T_x$  is the wall jet extreme temperature at the distance  $x$  from the diffuser,  $T_0$  is the supply temperature and  $T_R$  the room or the return temperature.  $K_{PT}$  is a constant for the wall jet.

The theory behind the wall jet assumes that the flow has a fully developed turbulent level, which also means that the normalized flow (velocity, turbulence) is independent of the Reynolds number. The general turbulent flow in ventilated rooms is often fully developed, see Hanel and Scholz (5), but diffusers may in some cases be used at low supply velocities giving a jet which is not fully developed. The equations (1), (2) and (3) are in this case used with  $D_p$ ,  $K_p$  and  $K_{PT}$ -factors which are functions of the supply velocity  $u_0$  or functions of the Reynolds number for the diffuser, see ref. (6).

A Reynolds number for the diffuser can be expressed by

$$Re = \frac{u_0 h}{\nu} \quad (4)$$

where  $\nu$  is the kinematic viscosity. This expression for the Reynolds number makes it possible to compare different sizes of the same type of diffuser, but it is not possible to compare two different designs.

When the air distribution system has to remove heat from a source in the room it will result in a flow with a thermal wall jet. The flow in the wall jet will in this case be dependent on the diffuser and the Archimedes number  $Ar$ , and it might be dependent on the Reynolds number at small supply velocities, but independent at higher velocity levels, see Müllers (7). The Archimedes number is given by

$$Ar = \frac{\beta g h \Delta T_0}{u_0^2} \quad (5)$$

where  $\beta$ ,  $g$  and  $\Delta T_0$  are the coefficients of thermal expansion, gravitational acceleration and temperature difference between return and supply, respectively. The Archimedes number will in this paper be expressed by the following factor

$$\frac{\Delta T_0 h}{u_0^2} \quad \left( \frac{Ks^2}{m} \right) \quad (6)$$

A three-dimensional jet can be expected far downstream in the flow from the diffuser with the small width. This will influence the velocity  $u_x$  and the  $T_x$ , and the velocity will in this case be expressed by the following equation (7) instead of equation (2)

$$\frac{u_x}{u_0} = K_a \frac{\sqrt{a_0}}{x+x_0} \quad (7)$$

$a_0$  is the supply area and  $K_a$  is a constant. The equation shows that the velocity ratio  $u_x/u_0$  is proportional to  $1/x$ , which is typical of a three-dimensional wall jet.

#### MEASUREMENTS AND DISCUSSION

All the measurements are made in a room which fulfils the Swedish regulation SP VVS 17 1973 on "Test of supply and return openings". The room dimensions are 12 m × 12 m × 3 m and the diffusers are mounted in the ceiling 6 m from each side wall.

#### SLOT HEIGHT

The slot height  $h$  and the supply velocity  $u_0$  are to be typical values for determination of the momentum flow from the slot diffuser.

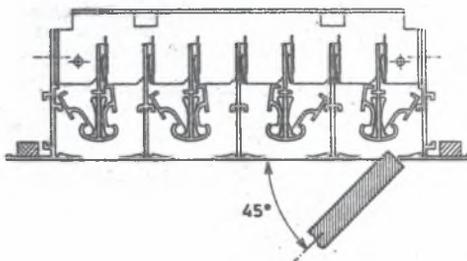


Fig. 2. Cross section of the ceiling-mounted slot diffuser and location of the hot wire instrument for measuring the supply velocity.

Rys. 2. Przekrój szczelinowego nawiewnika sufitowego oraz umiejscowienie anemometru z gorącym drutem służącego do pomiaru prędkości nawiewania

Fig. 2 shows the location of the hot wire instrument for measuring a supply velocity. This location of the instrument gives a maximum value, and the supply velocity  $u_0$  is found as the mean value of more measurements along the slot. The slot height is found from the equation

$$h = 0.001 \frac{q_0}{\ell \cdot u_0} \quad (\text{m}) \quad (8)$$

where  $q_0$  ( $\ell/\text{s}$ ) is the supply flow from the slot diffuser in the given direction and  $\ell$  (m) is the slot width. (The slot height  $h$  is thus different from the geometrical openings in the diffuser).

It is important to use the same measuring points for all determinations of  $u_0$  in different experiments.

#### ISOTHERMAL WALL JET FROM THE SLA 4-180 DIFFUSER

The velocity profiles are measured at different distances from the diffuser and  $u_x$ ,  $\delta$  and  $x_0$  are obtained from the measurements.  $K_p$  is established from a determination of the maximum velocity  $u_x$  as a function of the distance  $x$  from the diffuser. It is convenient to ignore the distance  $x_0$  to the virtual origin because it is small compared to the length of the jet. All the  $k_p$ -values in this paper are therefore calculated for  $x_0$  equal to zero ( $x_0 = 0.0$  in equation (2) and (7)).

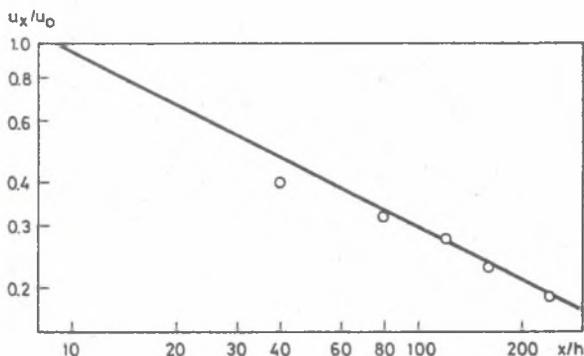


Fig. 3. Velocity decay in the isothermal wall jet from a slot diffuser with large width,  $\ell = 1.80$  m. The diffuser is adjusted to two horizontal wall jets,  $q_0 = 66$   $\ell/\text{s}$  in the measured direction

Rys. 3. Spadek prędkości w izotermicznym strumieniu przyściennym ze szczelinowego nawiewnika o dużej szerokości,  $\ell = 1,80$  m. Z nawiewnika rozchodzą się dwa poziome strumienie przyścienne,  $q_0 = 66$   $\ell/\text{s}$  w mierzonym kierunku

The diffuser is adjusted to two horizontal wall jets in opposite directions in the measurements.

The measurements on the diffuser with large width show on average a  $K_p$ -factor of 2.8. The value is rather independent of the Reynolds number for flows between 52 and 99 l/s. Fig. 3 shows a typical set of measurements. The velocity is proportional to  $1/\sqrt{x}$  over the whole distance  $x$ , as should be expected in a two-dimensional wall jet. (The slope of the line in fig. 3 is equal to -0.5).

#### ISOTHERMAL WALL JET FROM THE SLA 4-60 DIFFUSER

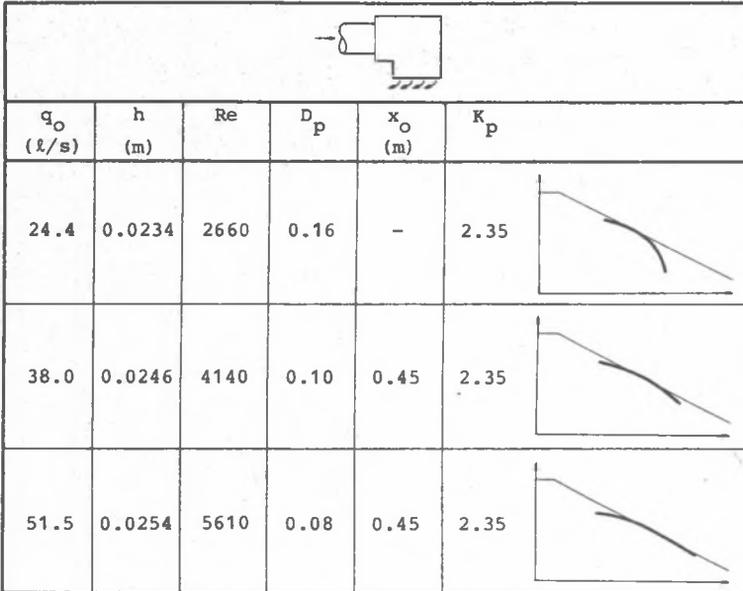


Fig. 4. Measurements of the isothermal wall jet from a slot diffuser with small width,  $l = 0.6$  m. The diffuser is adjusted for a single horizontal wall jet.

Rys. 4. Pomiary izotermicznego strumienia przyściennego z nawiewnika szczelinowego o małej szerokości,  $l = 0,6$  m; Z nawiewnika otrzymywany jest pojedynczy poziomy strumień przyścienny

Fig. 4 shows the measurements on the slot diffuser with small width,  $l = 0.6$  m. The diffuser is adjusted for a single horizontal wall jet. It should first be observed that the growth rate  $D_p$  is a significant function of the Reynolds number. A  $D_p$ -value of 0.16 is rather high, and the small sketch of velocity versus distance shows an atypical velocity decay for a two-dimensional wall jet. The flow is not fully developed, but it is still advantageous to use the wall jet theory because velocities calculated according to equation (2) are higher than or equal to the measured velocities. Therefore they will be safe

values for design procedures. The  $D_p$ -values and the velocity decay for an increased flow ( $q_0 = 38.0$  and  $51.5$  l/s) are more typical for a fully developed two-dimensional wall jet, references (2), (4) and (8).

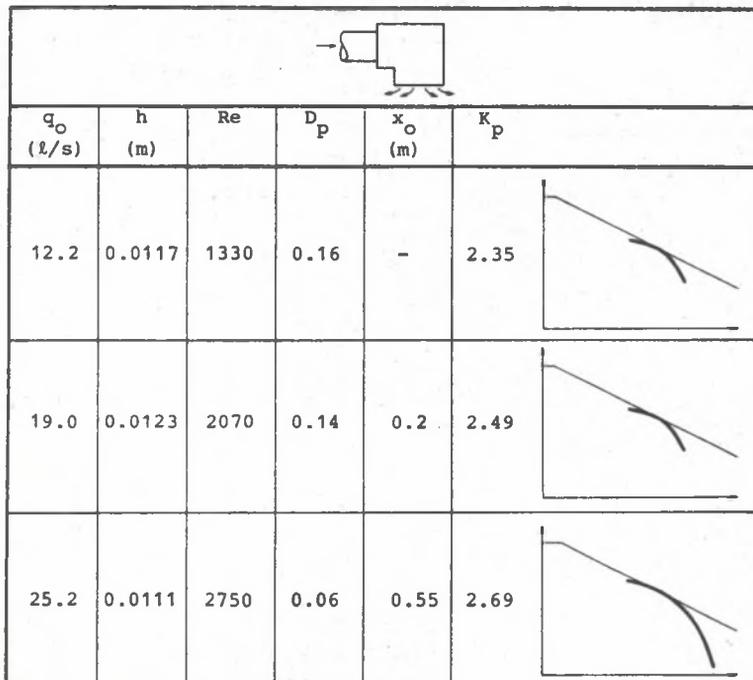


Fig. 5. Measurements of the isothermal wall jet from a slot diffuser with small width,  $l = 0.6$  m. The diffuser is adjusted to two horizontal wall jets.

Rys. 5. Pomiary izotermicznego strumienia przyściennego z nawiewnika szczelinowego o małej szerokości  $l = 0,6$  m. Z nawiewnika otrzymuje się dwa poziome strumienie przyścienne

Fig. 5 shows the measurements for the diffuser adjusted to two horizontal wall jets in opposite directions. The growth rate  $D_p$  is a function of the Reynolds number, and the value for the highest volume flow is typical for a fully developed wall jet. The sketches of the velocity versus distance show a velocity decay which exceeds  $1/\sqrt{x}$ . It may be assumed that the flow is changing to a three-dimensional flow, and an adoption to equation (7) gives a  $K_a$ -value of 4.1 for  $q_0 = 25.2$  l/s and  $x_0 = 0.0$  m

It is typical of the SLA 4-60 diffuser and the SLA 4-180 diffuser that the distance  $x_0/h$  is large compared to the values for a more conventional slot design and the  $K_p$ -factor is lower, see references (2), (4) and (8). A low  $K_p$ -factor means a low velocity at a given distance  $x$  and thus a high entrainment of air into the jet. The air distribution system can handle a high volume flow at low velocities in the room.

#### PENETRATION DEPTH

An undisturbed wall jet will penetrate the ventilated room in the case of isothermal flow and will entrain air from the occupied zone to induce recirculation air movement in the room. This picture will change when a thermal load is supplied to the room. The supply temperature will be reduced and the load may reach a level such that the wall jet will separate from the ceiling at a distance  $x_s$  from the diffuser and flow down into the occupied zone. Situations with a short penetration depth are undesirable, because the jet may have a high velocity and a low temperature when it flows into the occupied zone, and a calculation of the penetration depth is thus a part of the design procedure of the air distribution system.

Grimitlin, ref. (9), has shown that the penetration depth for a cold two-dimensional wall jet is proportional to  $1/(Ar)^{2/3}$ . The measurements in fig. 6 confirm the linear relationship between  $x_s/h$  and  $1/(Ar)^{2/3}$ , for the short as well as for the wide diffuser.

An analysis of the forces acting on a non-isothermal horizontal wall jet leads to the following equation

$$\frac{x_s}{h} \sim \left( \frac{K_p^2}{D_p K_{pT}} \right)^{2/3} \left( \frac{u_0^2}{h \cdot \Delta T_0} \right)^{2/3} \quad (9)$$

If it is assumed that  $K_{pT}$  is proportional to  $K_p$  and that  $D_p$  is proportional to  $1/K_p^2$  (constant momentum flow in a wall jet) it is possible to set up the equation

$$\frac{x_s}{h} = K_{sp} \cdot K_p^2 \left( \frac{u_0^2}{h \cdot \Delta T_0} \right)^{2/3} \quad (10)$$

where  $K_{sp}$  is a constant dependent on parameters outside the wall jet, such as room dimensions, location of thermal load, etc.

Measurements by Hestad, ref. (10), give a  $K_{sp}$ -value of 1.5 in the case of an evenly distributed heat source along the floor. The measurements in this paper are made by the same type of heat load and they confirm the  $K_{sp}$ -value of 1.5 as indicated in fig. 6.

The practical use of equation (10) is complicated because the jet air flow from different diffusers has different flow patterns in the area where it leaves the ceiling region and penetrates into the occupied zone, see reference (11). The penetration depth  $x_s$  for the linear slot diffuser is measured as the distance up to the area where the entrainment flow meets the jet at the ceiling surface (separation line). The jet travels a further distance  $\Delta x_s$  before it flows down into the occupied zone, where  $\Delta x_s$  is typically about 2 - 2.5 m.

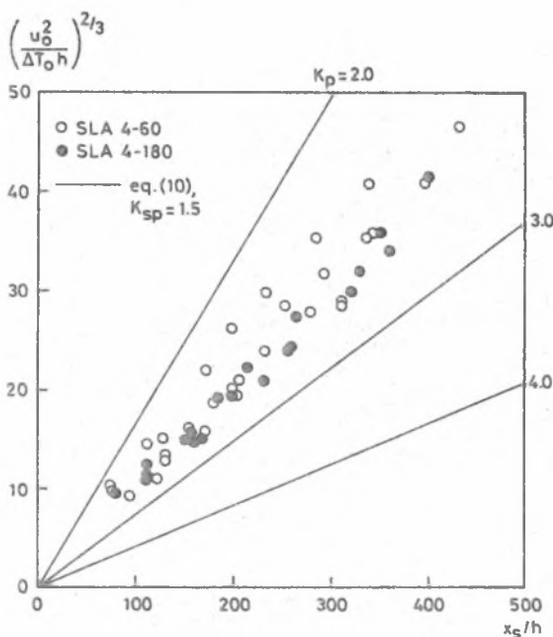


Fig. 6. Measurements of the normalized penetration depth  $x_s/h$  versus  $1/(Ar)^{2/3}$  for a wall jet established by the diffuser shown in fig. 1 and fig. 2. The diffuser is adjusted for two horizontal wall jets.

Rys. 6. Wyniki pomiarów znormalizowanego zasięgu strumienia  $x_s/h$  względem  $1/(Ar)^{2/3}$  dla strumienia przyściennego z nawiewnika przedstawionego na rysunkach 1 i 2. Z nawiewnika otrzymuje się dwa poziome strumienie przyścienne

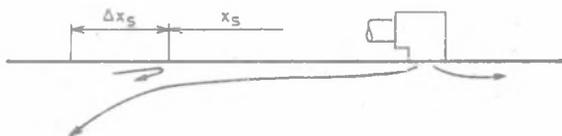


Fig. 7. Sketch of wall jet and penetration depth  $x_s$ .

Rys. 7. Schemat strumienia przyściennego i zasięgu strumienia  $x_s$

## CONCLUSIONS

Measurements on ceiling-mounted slot diffusers show that the flow along the ceiling can be described as a wall jet although the flow is dependent on the Reynolds number for most of the tests ( $1.5 < u_0 < 3.0$  m/s).

The velocity decay and the distance to the virtual origin are typically larger for this ceiling-mounted slot diffuser compared to the values for a more conventional slot design.

The wall jet from the diffuser with short width (0.6 m) shows a tendency towards three-dimensional flow over long distances from the diffuser.

The penetration depth is a function of the Archimedes number. Measurements show that the penetration depth  $x_s$  is proportional to  $1/(\text{Ar})^{2/3}$  and, furthermore, comparisons with other measurements show that the penetration depth  $x_s$  can be assumed to be proportional to the diffuser coefficient  $K_p$  in the second power.

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## ПОМИАРЫ WPŁYWU STRUMIENI KONWEKCYJNYCH Z SUFITOWYCH NAWIEWNIKÓW SZCZELINOWYCH

### Streszczenie

Strumień konwekcyjny występuje często jako część rozdziału powietrza w pomieszczeniach klimatyzowanych. Grubość strumienia przyściennego spowodowanego oddziaływaniem zimnej ściany zwiększa się z obciążeniem cieplnym i strumień może następnie odchylić się od sufitu w pewnej odległości od nawiewnika i przepłynąć do strefy przebywania.

W referacie przedstawiony zostanie wpływ liczb Archimedes'a i liczb Reynoldsa w odpowiednich warunkach na praktyczne zastosowanie klimatyzacji. Przeprowadzone pomiary zilustrują oddziaływanie wyporu na rozkład prędkości i temperatury w strumieniu przyściennym ze szczelinowego nawiewnika sufitowego, co jest istotną informacją gdy strumień przyścienny używany jest jako warunek brzegowy w programowaniu numerycznym. Pomiary zilustrują również strefę oddziaływania strumienia przyściennego spływającego z sufitu do pomieszczenia. Strefa oddziaływania dla tego typu nawiewnika zostanie porównana ze strefami oddziaływania dla innych rodzajów nawiewników i kratek nawiewnych.

## ИЗМЕРЕНИЯ ВЛИЯНИЯ КОНВЕКЦИОННЫХ СТРУЙ С ПОТОЛОЧНЫХ ЩЕЛЕВЫХ ВЕНТИЛЯТОРОВ

### Резюме

Конвекционный поток часто является частью распределения воздуха в вентилируемых помещениях. Ширина околостенной струи возникшей вследствие воздействия холодной стены растет с тепловой нагрузкой, струя может отклониться от потолка в некотором расстоянии от вентилятора и переплыть в зону пребывания.

В настоящей работе будет указано влияние чисел Архимеда и Рейнольдса в соответственных условиях на практическое применение кондиционирования воздуха. Проведенные измерения проиллюстрируют воздействие гидравлического подбора на распределение скорости и температуры в околостенной струе от щелевого потолочного вентилятора, это является существенной информацией когда околостенная струя употребляется в качестве краевых условий в численном программировании. Измерения проиллюстрируют также зону влияния околостенной струи попадающей от потолка в помещение. Зона влияния вентиляторов и приточных вентиляционных решеток.