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Turbulence Characteristics in Rooms Ventilated with a High Velocity Jet.

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Abstract

The measurements reported in this paper were carried out in a mock up of an office room, ventilated by a commercial supply air terminal consisting of 84 nozzles (characteristic dimension $\sqrt{A_s} = 0.0975$ m). The test room configuration was identical to the one used within the IEA Annex 20 work. Results from isothermal supply is reported. A constant-temperature hot-film anemometer with fast dynamic response was used to record the instantaneous velocities.

The following parameters were recorded

- Mean velocity
- Standard deviation (relative turbulence intensity)
- Turbulent integral length scale and microscale

The turbulent length scale was derived from the autocorrelation function.

The above parameters were recorded at the following locations:

1. At a *fixed* distance from the supply air terminal the *near ceiling velocity* was recorded at different flowrates (Reynolds number). The errors of the velocity readings due to additional heat losses to the the wall were corrected for. By this procedure we obtained the near wall velocity profile (wall function) in a room with normal surface roughness. Both the change in turbulent velocity scale (standard deviation) with distance from the ceiling and the change in turbulent length scale with velocity are reported.

2. At stations *along the perimeter* (ceiling-wall-floor) and at the point where the maximum mean velocity of the wall jet occurred. These measurements provided information regarding the velocity decay in the wall jet and the evolution of the turbulent length scales with distance from the terminal.

1 Introduction

Measurements of turbulence quantities in *free* jets is fairly abundant. One classical example is Wyganski I. & Fiedler H. (1969) and Gutmark E. & Wyganski I. (1976). The first paper is concerned with an axisymmetric jet whereas the last paper reports on a two-dimensional jet. Measurements of wall jets are less abundant, for a review on wall jets see Launder B.E. & Rodi W. (1983).

The more "scientific" orientated measurements of turbulence characteristics have been carried out under specially arranged laboratory situations. Measurements of turbulent quantities in ventilated spaces have been performed by several e.g. Hanzawa et al (1987), Kovanen et al (1987), Sandberg (1987). The main concern in these investigations were the conditions in the occupied space. The analysis of the velocity fluctuations was based on recorded spectral density. The present work is, however, concerned with measurements of the wall jet in an office room. The velocity fluctuations were analyzed by recording the autocorrelation function. All room surfaces had normal surface coating and surface roughness. The jet was issued from a commercial air terminal.

The present investigation was undertaken in order to extend the knowledge of turbulence in a real room situation. In particular the idea was to study the effect of the deflection of the jet that occurs at the corners of the room. Measurements were therefore carried out along the jet trajectory from the inlet to the occupied zone.

2 Test room and experimental procedure

Fig. 1 shows the testroom (WxLxH = 3.6x4.2x2.5 m) and the location of the supply air terminal

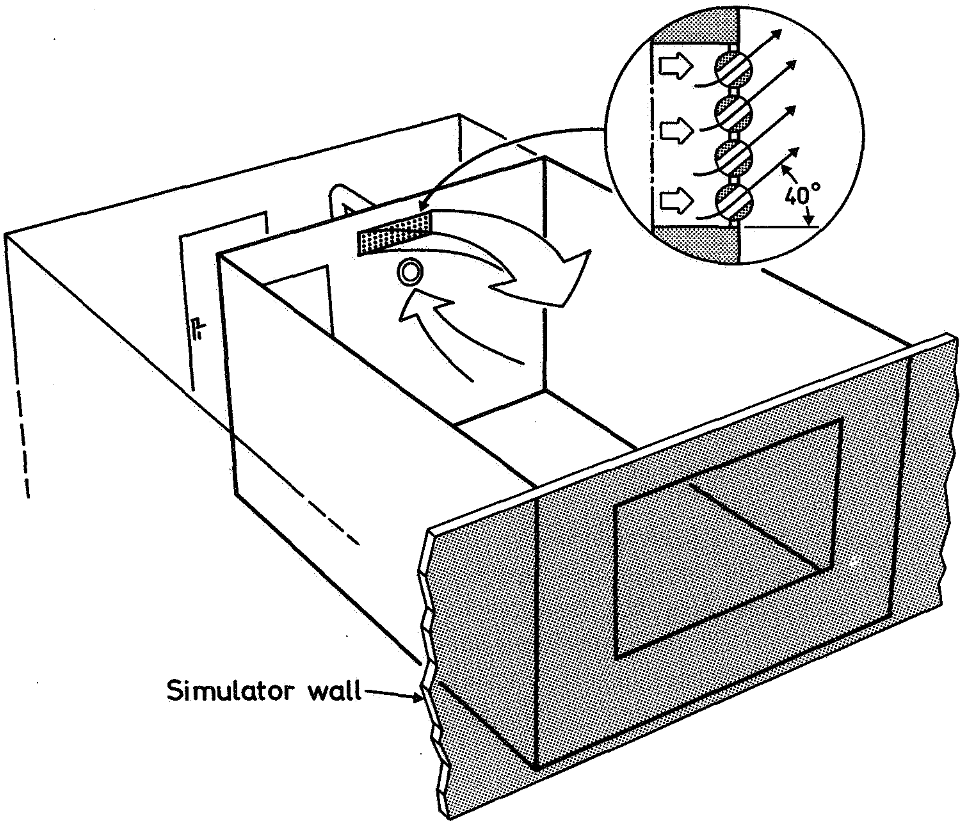


Figure 1 Test room

The supply air terminal consisted of a manifold of 84 small nozzles arranged in four rows and directed *upwards*. The total geometrical opening area A_s of all nozzles amounted to 0.0095 m^2 which gave a characteristic dimension $\sqrt{A_S}$ equal to 0.0975 m.

All velocities were recorded with a temperature compensated bridge (Dantec 56C14) provided with a hot flim probe (Dantec 55R76). The total number of samples collected at each measuring point amounted to 102 400. The sampling rate was 50 or 100 Hz which corresponds to a time of integration of 34 min and 17 min respectively. The signal was filtered at about 40 % of the sampling frequency.

The measurements were carried out in the vertical symmetry plane through the terminal. When the velocities were measured the anemometer was orientated perpendicular to the axis of the flow. All measurements were carried out at isothermal condition.

The experimental conditions are collected in table 1 below.

***Table 1** Listing of experimental parameters*

Flow rate (n) [room volumes/h]	Nominal supply velocity [m/s]	Re_d [1]
1.0	1.11	1 108
1.5	1.66	1 662
2.0	2.21	2 217
3.0	3.32	3 326
4.0	4.42	4 434
5.0	5.53	5 543
6.0	6.63	6 652

Nominal supply velocity is equal to the flow rate divided by the geometrical opening area. The discharge Reynolds number Re_d is based on nominal velocity and the diameter of the nozzle.

We see from the table that the Reynolds number is very low at the lower flow rates. Therefore one can surmise flow in the room to be Reynolds number dependant. Malmström (1974) has show that the spread of a jet to be Reynolds number dependent at those low values on the Reynolds number as one frequently encounters in ventilation engineering. In the literature the minimum Reynolds number for the flow to be Reynolds number independent is reported to lie around $Re_d \approx 10^4$.

Skovgaard et al (1990) recorded the effective area of the same terminal as ours and found the effective area to be Reynolds number dependant. The effective area did not bacome equal to the nominal area until $Re_d \approx 8\ 000$.

3 Measurements carried out along the perimeter of the room

Mean velocity and the standard deviation

Fig. 2 shows the mean velocity and standard deviation recorded very close to one of the 84 nozzles of the terminal.

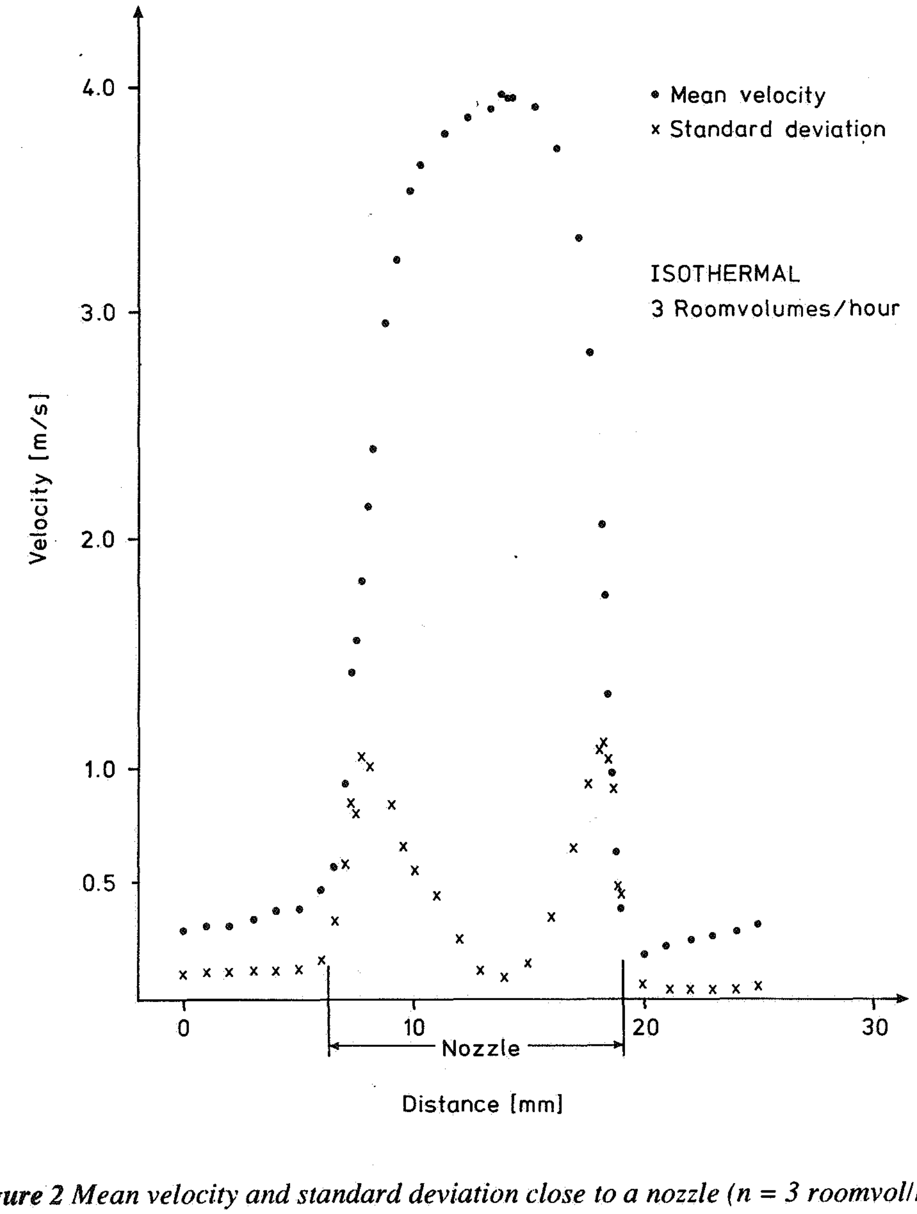


Figure 2 Mean velocity and standard deviation close to a nozzle (n = 3 roomvol/h)

The measurements shown in Fig. 2 were carried out in the development region of the jet and the maximum of the turbulence occurs at the center of the mixing region.

Fig. 3 shows the velocities recorded along the perimeter of the room in a vertical plane through the supply.

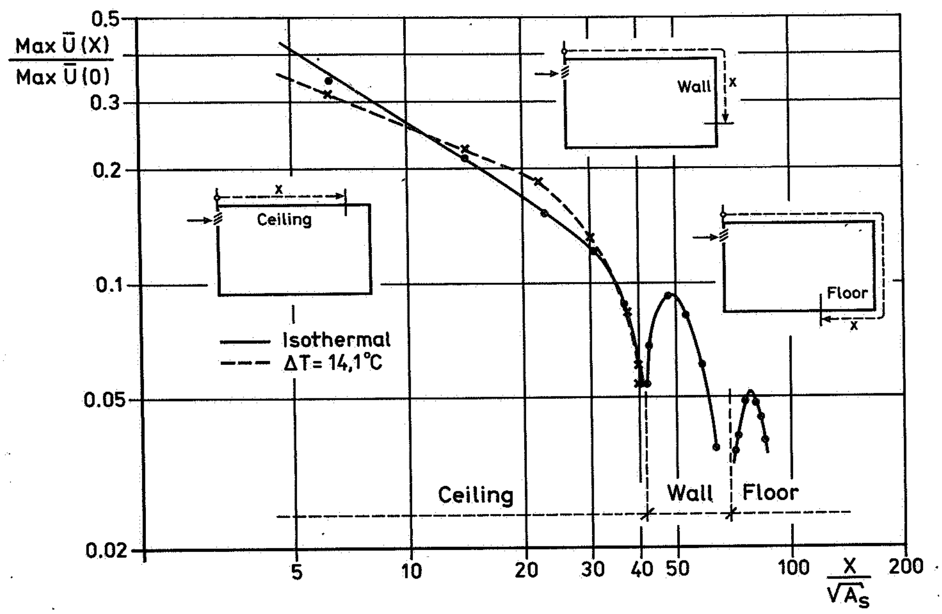


***Figure 3** Maximum mean velocity along the perimeter of the room (n = 3 roomvol/h)*

We see that we have a "short room" so the circulation in the room is set up by a wall jet that follows the perimeter of the room. Fig. 4 shows the maximum velocity in the jet as a function of the distance from the terminal. The data is given in non-dimensional form so the recorded velocity has been divided by the nominal velocity at the inlet and the distance from the outlet has been divided by the square-root of the free opening area.

When the air stream arrives at the opposite wall the velocities in the jet decrease and the thickness of the jet increases. The pressure increases at the wall and the flow is retarded and deflected downwards along the wall. The flow is at first accelerated by the higher pressure and a maximum velocity is attained. After this point the flow decelerates again. We see that the deceleration is now faster than that along the ceiling. At the lower corner the procedure is repeated again and the maximum velocity in the occupied zone is attained at same distance from the wall. The behaviour of the jet can be described as the jet restarting at each corner.

Waschke (1974) studied the effect of deflection of a radial wall jet that was supplied under the ceiling. He showed that the jet along the wall could be considered as a radial jet but now starting from a new virtual origin that did not coincide with the virtual origin of the ceiling jet.

The theory which is valid for flows in infinite or semi-infinite spaces where the ambient is quiescent, predicts that the velocity decay should follow the relation X^{-1}. However, the decay is less rapid and follows approximately the relation $X^{-0.62}$. The deviation from the theory must be due to the fact that the jet is supplied into a finite enclosure. It can be concluded from the measurements that the lateral expansion of the jet is not constrained by the sidewalls. One can surmise that the counterflow set up in the room slows down the decay of the maximum velocity. The jet is therefore expanding into an ambient that is moving. For a so called *weak jet* expanding into an ambient that moves (compound jet) in the same direction as the jet, the theory predicts that the the decay shall follow the relation

$X^{-2/3}$, see Rajartmam N. (1976). This is very close to our result. This may however be a mere coincidence since it is not clear if the theory for compound jets is applicable in this case were the jet itself that sets up the air motion. We can at least conclude that we do not expect theories valid for infinite spaces to be valid in enclosures.

Measurements reported by Skovgaard et al (1990) in the same room configuration and with the same type of terminals show a similar result.

Fig. 4 shows, as a function of flow rate, the maximum mean velocity at two stations. The first point is located under the ceiling 2.2 m from the supply air terminal whereas the second one is located where the maximum mean velocity did occur in the occupied space. The maximum velocity at the floor occurred, at all flow rates, 3.5 m from the backwall which corresponds to 0.7 m from the facade wall.

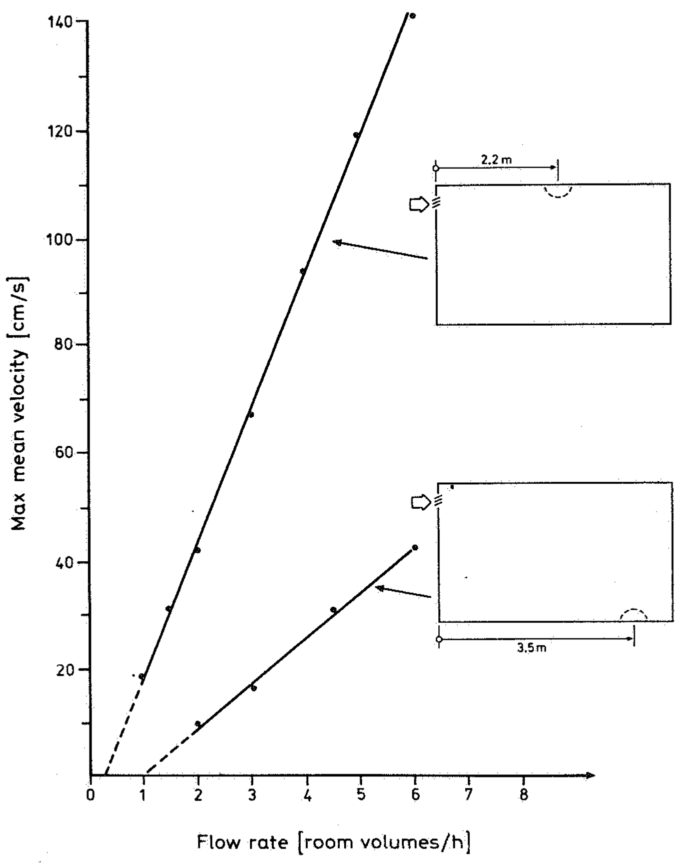


***Figure 4** Maximum mean velocity as a function of flow rate*

By extrapolating the fitted straight lines in Fig. 4 toward lower flow rates we see that they do not pass through the origin. The deviation is larger at the floor-level. This behaviour, that the room velocities at low flow rates are not proportional to the inlet velocities has earlier been documented by Nielsen P V (?).

Autocorrelation measurements and turbulence scales

The correlation of the same velocity component at a fixed point, x_0, is known as the autocorrelation. By definition, the normalized autocorrelation for the velocity fluctuations, u', is given by

$$R_{\Delta t}(x_0,\Delta t) = \frac{\overline{u'(x_0,t)u'(x_0,t+\Delta t)}}{\overline{u'^2}} \tag{1}$$

Where Δt is the time separation. When the turbulent motion is occurring in a flow with a large mean velocity $\overline{U}$, it is possible for the turbulence to be advected past the point of measurement more rapidly than the pattern of fluctuation is changing. When this is the case the autocorrelation function with time separation Δt can be interpreted as a spatial correlation where separation in distance is equal to (Taylor's transformation):

$$\Delta x = -\overline{U}\Delta t \tag{2}$$

The above assumption means that the transportation velocity for the turbulence is set approximately equal to the the average velocity, $\overline{U}$. We obtain

$$R_{\Delta x}(x_0,\Delta x) = R_{\Delta t}(x_0,\Delta t) \tag{3}$$

From the autocorrelation measurements the *integral* scale, Λ_t, is obtained as

$$\Lambda_t = \int_0^\infty R_{\Delta t}(x_0,\Delta t)d(\Delta t) \tag{4}$$

From our measurements the integral scale was calculated by taking the value on the time axis for which the normalized autocorrelation function had declined to e^{-1}, see Fig. 5. This integral-scale is denoted by Λ_t^e and Λ_x^e (see below).

The Taylor microscale λ_t is defined as:

$$\lambda_t = (2\overline{u'^2}/\overline{(\frac{\partial u'}{\partial t})^2})^{1/2} \tag{5}$$

The turbulence scales obtained from the measurements carried out at the same point have then been transformed to turbulence scales for spatial separation by multiplying by the average velocity:

$$\Lambda_x = \overline{U}\Lambda_t \quad \text{and } \lambda_x = \overline{U}\lambda_t \tag{6}$$

The above transformation can be regarded as purely formal because we can not take for granted that the Taylor hypothesis is strictly applicable to this type of flow since the relative turbulence intensity lies around 20-30 %, which is quite high.

The microscale λ_t has been obtained by fitting the to the parabola

$$1 - R_{\Delta t}(\Delta t) = \left(\frac{\Delta t}{\lambda_t}\right)^2 \tag{7a}$$

to the data close to $\Delta t=0$. This was done by using the equivalent relation

$$\ln(1 - R_{\Delta t}(\Delta t)) = 2\ln\left(\frac{\Delta t}{\lambda_t}\right) \tag{7b}$$

which was plotted in a graph. This method is not very accurate, there are better methods, however it gives the order of magnitude of the microscale.

The autocorrelation function, $R_{\Delta t}$, was recorded at the same point as the data presented in Fig. 3. The next figure shows the autocorrelation function whith a non-dimensional x-axis $\left(\frac{\Delta x}{x} = \frac{\overline{U}\Delta t}{x}\right)$

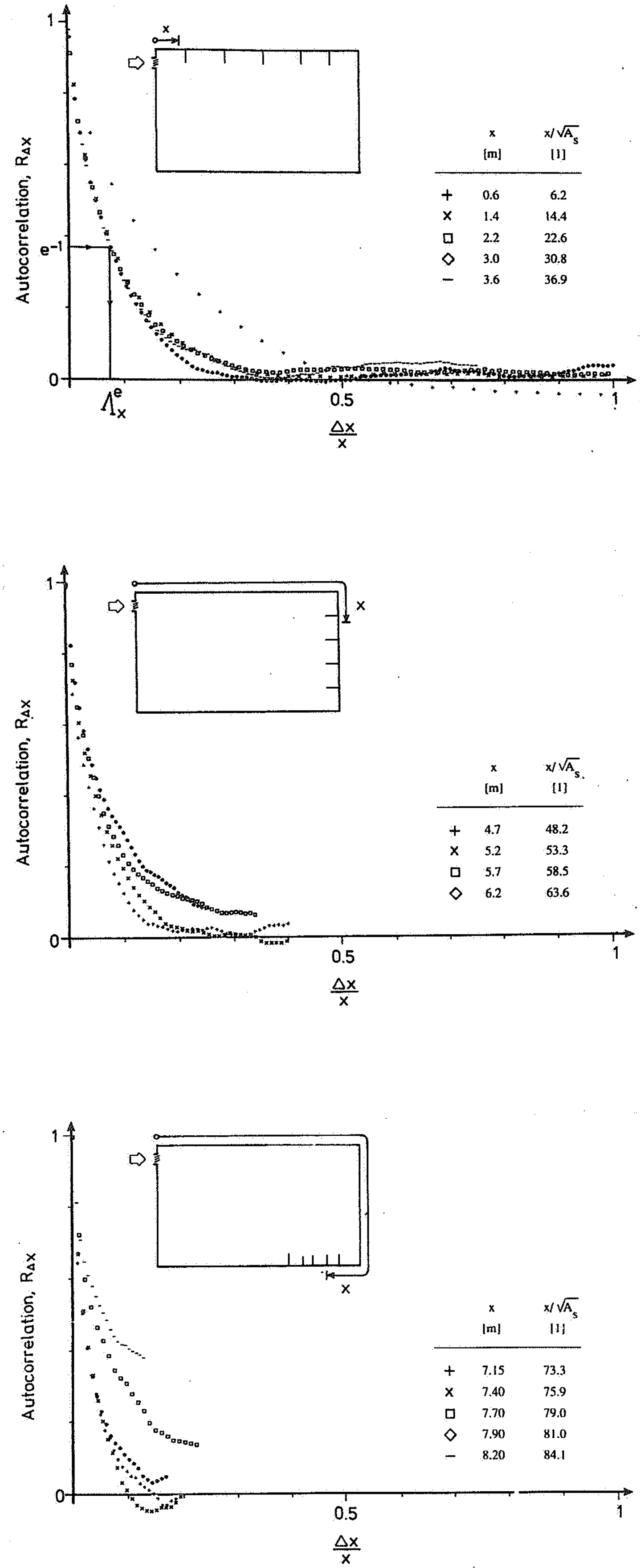


***Figure 5** Autocorrelation function on the jet centre-line. From above*
- Ceiling
- Wall
- Floor

It appears from Fig. 5 that under the ceiling (apart from close to the terminal) the curves collapse on the same line so the structure is self- preserving from ($x/\sqrt{A_s}$=14.4). The integral-scale for the expansion of the jet under the ceiling became, Λ_x^e = 0.076x. This value is within the range reported by others, see data compiled by Wygnanski & Fiedler (1969).

The autocorrelation functions for the first two measurement points on the wall differ from the function recorded under the ceiling. However, at the following two measuring points on the wall ($x/\sqrt{A_s}$ =58.5 and 63.6) the autocorrelation function does coincide reasonably well with that recorded under the ceiling.

When we come to the measuring points on the floor one can no longer trace any resemblance with the autocorrelation functions recorded further upstream. The behaviour is quite erratic.

The next figure shows the integralscale, Λ_x^e, at the same points as in Fig. 5.

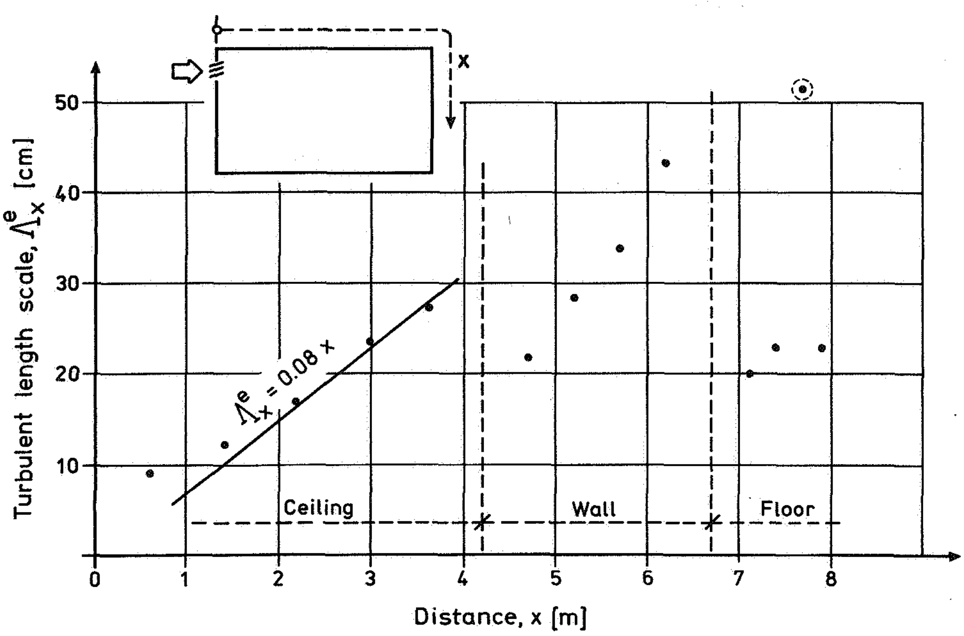


Figure 6 Integralscale Λ_x^e on the jet centre-line

Close to the terminal the integralscale is around 10 cm which, as expected, is a value close to the characteristic dimension of the terminal, $\sqrt{A_s}$= 9.8 cm. Also as expected the integralscale first grows linearly with distance from the supply air terminal. After the jet has been deflected at the corner ceiling wall the integralscale again grows linearly but now "starts" from a lower value. The behaviour is repeated in the next corner. The behaviour of the integralscale along the floor is, however, more erratic.

Table 2 shows the Taylor microscale. The microscale could only be calculated when the velocity had decayed to around 20 cm/s. At higher velocities the sampling frequency, 50 Hz, was too low to resolve the autocorrelation function close to Δt=0.

Table 2 Taylor microscale and ratio between integral and micro scales

X [m]	$X/\sqrt{A_s}$ [1]	λ_x^e [cm]	$\frac{\Lambda_x^e}{\lambda_x^e}$	Location
5.7	58.7	4.7	7.2	Wall
6.2	63.6	5.2	8.3	Wall
7.15	73.3	3.6	5.7	Floor
7.40	75.9	4.1	5.6	Floor
7.70	79.0	5.9	8.9[1]	Floor
7.90	81.0	4.6	5.0	Floor

4 Measurements carried out at a fixed station

All the measurements reported in this subsection was recorded at ceiling level 2.2 m ($x/\sqrt{A_s}$= 22.6) from the terminal.

Fig. 7 shows the mean velocity, turbulent fluctuation and the turbulent integral scale. The first two quantities have been scaled by the maximum mean velocity (max $\bar{U}$). In Fig. 7 $b_{1/2}$ denotes the half width of the jet.

1. This value is probably too large because the recorded integral-scale is too large, see Fig. 6 (indicated by a dashed circle).

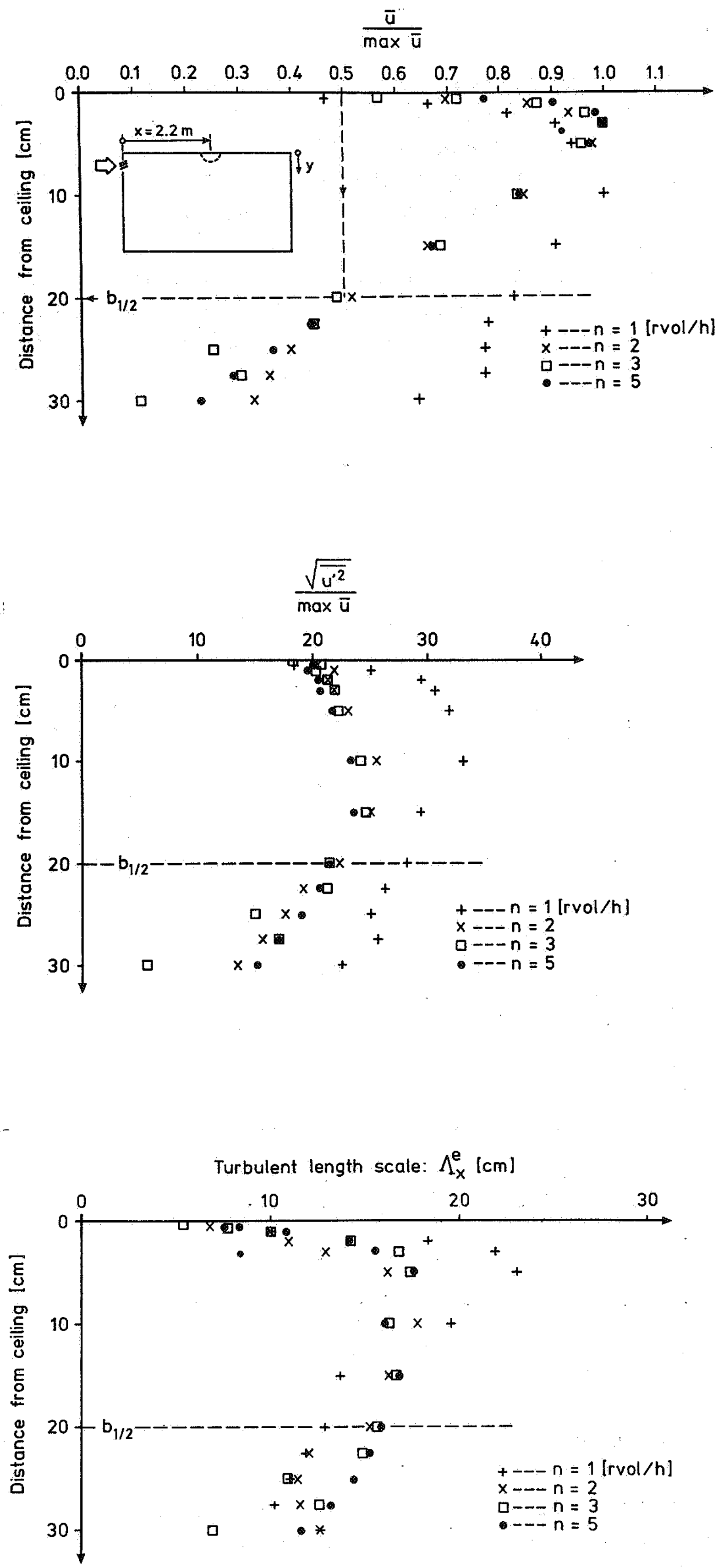


***Figure 7** Recorded distribution of:*

Streamwise mean velocity ($\overline{U}$)
Streamwise turbulent fluctuations ($\sqrt{u'^2}$)
Streamwise integral length scale

It appears from Fig. 7 that the mean velocity and the turbulent fluctuations are independent of the flow rate from n = 2 room volumes/h (Re_d = 2 217). The turbulent length scale does not become independent of flow rate until n = 3 roomvolumes/h (Re_d = 3326). In the literature axisymmetric jets are said to be self-similar when $x/\sqrt{A_s} > 40$. The mean velocity fields become self-similar closer to the supply than the turbulent fluctuations that require a longer distance. We are closer than this value and we cannot therefore conclude that the jet behaves in a self-similar manner, although the shape of the distribution does not change with increasing flow rate. Fig. 8 shows the turbulent time scale, λ_t^e, recorded at the point where the maximum mean velocity occurs (around 30 mm under the ceiling).

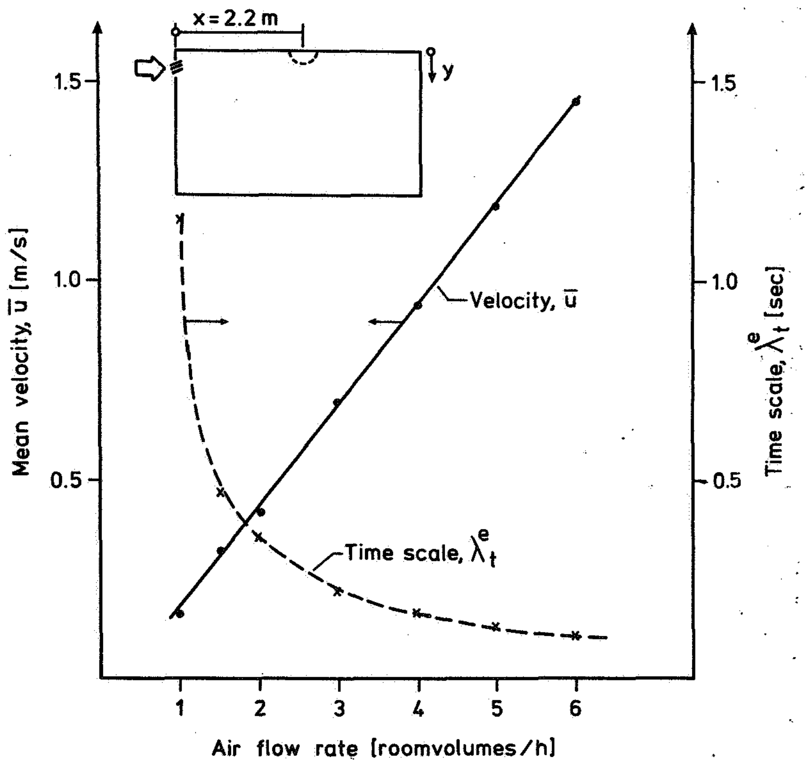


Figure 8 Turbulent time scale, λ_t^e, as a function of the mean velocity

As expected the time scale is inversely proportional to the velocity because the integral length scale, $\Lambda_x^e = \overline{U} \cdot \lambda_t^e$, is constant (in this case $\Lambda_x^e \approx 15$ cm)

Near wall measurements

The most important near wall velocity scale is the friction velocity $U_* = \sqrt{\frac{\tau}{\rho}}$. An attempt was made to record the shear stress, τ, at the room surface with a modified Preston Tube. However, this attempt failed because the velocity was too low for the calibration curve of the Preston Tube to be valid. This highlights the common problem when making velocity measurements in ventilated rooms, the velocities are so low that techniques developed within other areas are frequently not applicable.

The problem of recording velocities with hot-wire anemometers near surfaces is well known. Additional heat losses to the wall result in too high velocities. Therefore we used a computational technique described by Bhatia J C et al (1982) for correction of the recorded near surface velocity. The magnitude of the shear stress was obtained from the slope of a graph of velocity versus distance from the surface. The thickness parameter, l, ($l = v/U_*$) amounted to: n = 1.5 roomvol/h, l ≈ 0.5 mm: n = 3 roomvol/h, l ≈ 0.3 mm. Fig. 9 shows the near ceiling measurements presented in standard wall coordinates

$$(U^+ = \frac{\overline{U}}{U_*}, Y^+ = \frac{Y}{l})$$

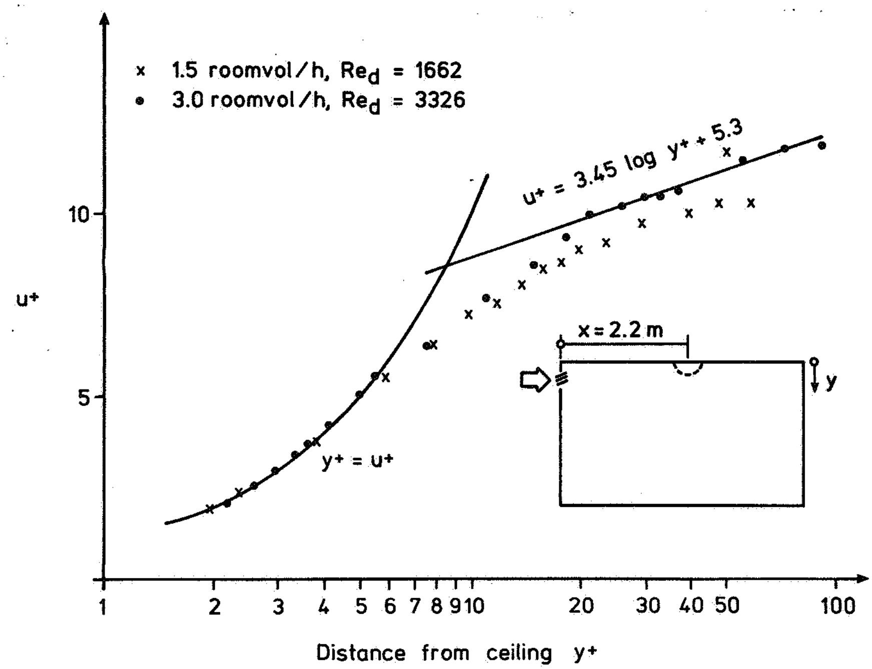
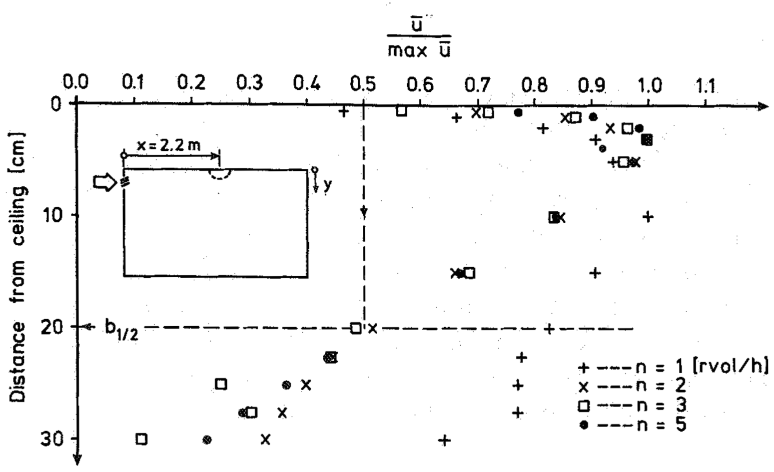


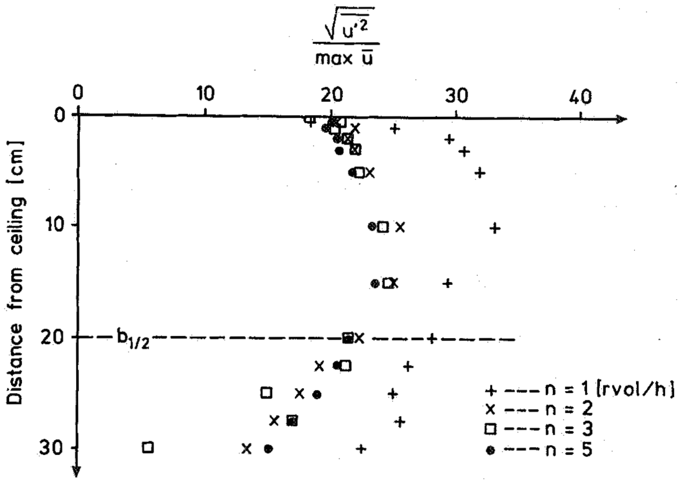
***Figure 9** Wall function*

It appears in Fig. 9 that the wall function is Reynolds number dependent which shows that the flow is in a transitional region. The coefficient in front of log y^+ was 3.45 in our measurements which is far from the "universally" adopted value of 5.5. This difference may be due to one or combination of the following factors:

- Error in the wall shear stress and subsequently U_*
- The curve fitted over a short region
- Developing flow

Fig. 10 shows the rms-value of the streamwise fluctuations scaled by the friction velocity.





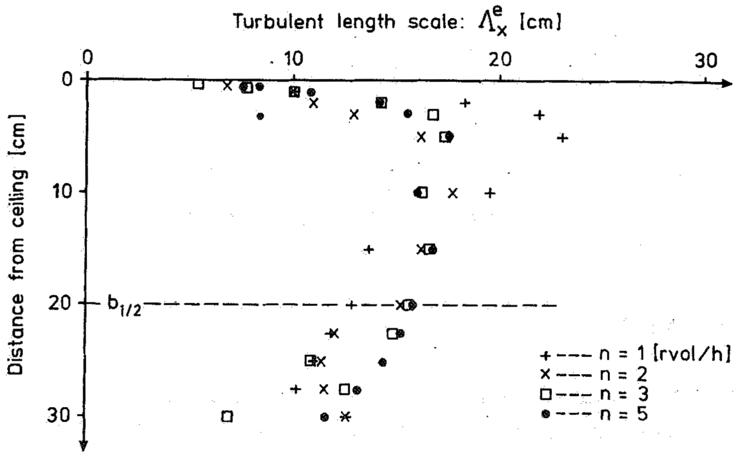


Figure 7 *Recorded distribution of:*

Streamwise mean velocity ($\overline{U}$)
Streamwise turbulent fluctuations ($\sqrt{\overline{u'^2}}$)
Streamwise integral length scale

We see that the relative turbulence intensity at the lower flow rates decreases with increasing flow rates. . This trend is probably a real effect whereas for flow rates higher than 3 roomvolumes per hour the scatter in data reflects uncertainties in the measurements. Finally Fig. 12 shows the turbulent length scale near the wall.

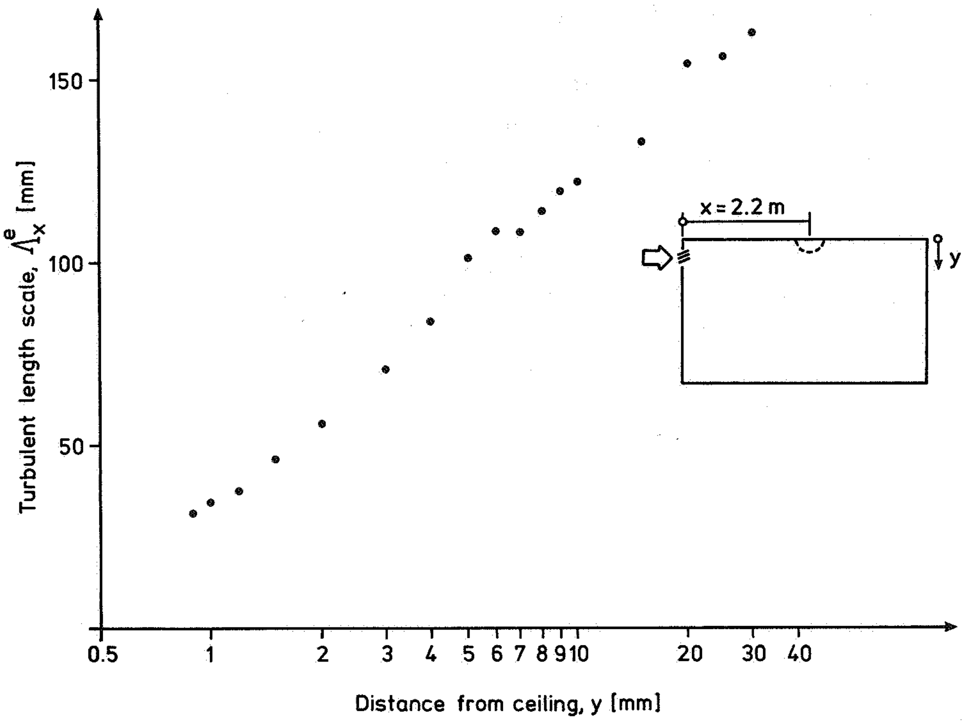


Figure 12 *Turbulent length scale (n = 3 roomvolumes/h)*

Conclusions

Measurements at a *fixed* station under the ceiling ($x/\sqrt{A_s} = 22.6$), carried out at different flow rates, showed that the streamwise mean velocity and turbulence intensities became independent of the discharge (based on the diameter of the nozzles) Reynolds number (Re_d) for $Re_d > 2\,200$. The corresponding specific flow rate was 2 roomvolumes/hour. The integral length scale became independent of the Reynolds number from $Re_d \approx 3\,300$ (flow rate, 3 roomvolumes/h).

Measurements *near the wall* showed that for $y^+ > 10$ both the mean velocity and the turbulent fluctuations were dependent on the Reynolds number.

Measurements carried out on the jet centre-line (location of max mean velocity) *along the perimeter* of the room (flow rate 3 roomvolumes/h, discharge Reynolds number 3326) showed;

- The *decay of the velocity* in the jet does not coincide with any "classical" formula for a jet in an infinite quiescent ambient

- The *turbulent length scale*, when *close to the terminal*, became equal to the characteristic dimension of the terminal

- Under the ceiling the *turbulent length scale*, Λ_{ex}^{e}, obeys the following relation with the distance, x, from the terminal, $\Lambda_{x} = 0.076x$

- The *turbulent length scale* became *in the occupied space* approximately twice the characteristic dimensions of the terminal

- The general behaviour of the jet, with regard to the decay of the mean velocity and expansion of the turbulent length scale, along the perimeter of the room can be described as that the jet "restarts" after it has decelerated and been deflected at a corner.

The general conclusions of the findings is that in the case where the jet is supplied into a finite ambient and in particular where the jet is constrained to change direction at room corners has a strong influence on jet behaviour. In order to be of any success at the design stage for assessing the velocities in the occupied space, this room influence must be considered in the testing procedures of supply air terminals.

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