Some Confinement Effects of Jets in Ventilated Rooms

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ABSTRACT

In the first part of this paper, the physical conservation laws valid for flows in rooms are introduced and the determinants for jet flows in rooms are identified. Experimental studies of both three- and two-dimensional jets in rooms are presented. Although the traditional wall jet theory, based on the expansion of a jet in an infinite ambient, often is useful in room airflow, these studies show that there may be confinement phenomena that have strong influence on jet development. There are losses in kinematic momentum of the jet due to surface friction and recirculation effects (exchange of momentum between the jet and the moving ambient). For a two-dimensional jet, the velocity decay and jet spreading rate, i.e., the thickness of the jet in an enclosure, are larger than for traditional wall jets, and the decay rate of the velocity became 0.43, which is less than the theoretical value 0.5.

A new testing procedure for supply devices, which considers the effect of the enclosing room surfaces, is proposed.

INTRODUCTION

In test procedures currently in use for supply devices, the tests are done in rooms that usually are larger than the room where the supply devices finally are installed. Therefore, it is of practical interest to study the difference between properties of jets under the ideal test conditions of a laboratory and the properties of jets issuing from the same supply device that is located in a room in a building. The first part of this paper discusses the basic physical conservation laws valid for flow in rooms. The determinants for jet flows in rooms are identified. Then experimental results showing the properties of real jets in rooms are presented and discussed.

SOME BASIC CONCEPTS AND CONSERVATION LAWS

Some basic concepts are introduced in this section (a thorough discussion of these subjects can be found in, e.g., Etheridge and Sandberg [1996]).

Consider a room with varied locations of supply and extract terminals. The net flow rate is conserved, i.e., the flow rate obtained by integrating the mean velocity over the room's cross-sectional area, A_{room}, in Figure 1 is equal to

$$\text{Case a} \quad \int_{A_{room}} \bar{U}dA = q_v \qquad \text{Case b} \quad \int_{A_{room}} \bar{U}dA = 0 \tag{1}$$

When neglecting friction at room surfaces, the *x*-component of the momentum equation takes the following form when integrated over A_{room} (buoyancy forces appear only in the y-component):

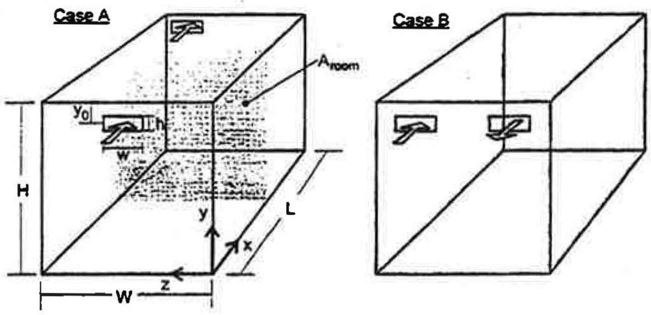

Figure 1 Two alternative locations of supply and extract air terminals.

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$$\int_{A_{room}} (\bar{p} + \rho(\bar{U}^2 + \overline{U'^2}) dA = \text{Constant} \quad (2)$$

This expression, which includes the pressure, is sometimes called the *flow force.* As will be shown later, in small rooms there are strong pressure gradients that cannot be neglected. In classical jet theory, where the jet is expanding in an infinite medium, one assumes that there are no pressure gradients. Furthermore, the total kinematic momentum flux is the sum of the momentum flux of the mean velocity field $M_{\bar{U}}$ and the momentum flux $M_{U'}$ due to the turbulent fluctuations U'.

$$\rho \int_{A_{jet}} (\bar{U}^2 + \overline{U'^2}) dA \equiv M_{\bar{U}} + M_{U'} = M_{\bar{U}}(1+\gamma) \quad (3)$$

When neglecting friction against room surfaces, the momentum equation in the x-direction for a jet is

$$\int_{A_{jet}} (\bar{p} + M_{\bar{U}} + M_{U'}) dA = \text{Not constant} \quad (4)$$

For the whole room flow, the flow force (Equation 2) is conserved, but this is not true for the jet flow because, due to entrainment of air into the jet, there is a transfer of momentum that changes the momentum of the jet during its course.

In the model of jet flow used in ventilation applications, one uses the following relation for representing the velocity decay:

$$\frac{\bar{U}_c}{U(0)} = f\left(\frac{(x+x_0)^n}{\sqrt{A_s}}, Re_{\sqrt{A_s}}, \frac{l_m}{\sqrt{A_s}}\right) \quad (5)$$

where $U(0)$ is a characteristic velocity representing the initial (kinematic) momentum flux and n is an exponent ($n = -1$ for an ideal axisymmetric jet and $-1/2$ for an ideal plane jet). The Reynolds number appears because, due to the low Reynolds numbers that usually occur in ventilation, there may be some Reynolds number dependence. The quantity l_m is the thermal length. The thermal length considers the relative strength of the momentum flux expressed as the specific momentum flux, m, and buoyancy, expressed in terms of the specific buoyancy flux, B. The thermal length is also given below in terms of the densiometric Archimedes number.

Two-dimensional jet Three-dimensional jet

$$l_m = \frac{m}{B^{2/3}} = \frac{Ar(0)^{2/3}}{\sqrt{A_s}} \qquad l_m = \frac{m^{3/4}}{B^{1/2}} = \frac{\sqrt{Ar(0)}}{\sqrt{A_s}} \quad (6)$$

The thermal length is the distance from the supply to where the buoyancy becomes important. For an isothermal jet, it is infinite. In a room, one must add a number of factors to (Equation 5) that may influence the development of the jet.

$$\frac{\bar{U}_c}{U(0)} = f\left(\frac{y_0}{\sqrt{A_s}}, \frac{\sqrt{A_s}}{\sqrt{A_e}}, \frac{\sqrt{A_s}}{H}, \frac{L}{H}, \frac{L}{W}, C_f, \frac{A_{jet}}{W \times H}, \frac{l_m}{L}, \frac{l_m}{\sqrt{A_s}}\right) \quad (7)$$

Equation 7 only lists factors related purely to the room geometry and conditions at the supply. There are other factors of importance, such as the occurrence of obstacles and location of sources and sinks of heat. Despite the influence of these additional factors, it may be that we can still use Equation 5 as a model for jet flow in an enclosure but now with a modified exponent n and another distance x_0 to the virtual origin and constant of proportionality.

For mixing ventilation, the relative size of the terminals is not generally an important parameter because it does not vary greatly. Similarly, the relative sizes of terminal and room dimensions are usually small, typically on the order of 0.04. The position of terminals is important. One reason for this with supply terminals is that the proximity to a surface leads to the formation of a wall jet and a subsequent loss of momentum due to friction. The distance from the supply to the location of the point of attachment to the surface is a function of $\frac{y_0}{\sqrt{A_s}}$ and $\frac{l_m}{\sqrt{A_s}}$. The ratio L/H determines if the room is "short" or "long." In a long room, the jet separates from the ceiling when $\frac{A_{jet}}{W \times H}$ is sufficiently large. The distance to where the jet separates from the ceiling is dependent on the locations of the supply and extract devices. For terminals located on opposite sides, the distance to where it will separate will be prolonged. A separation from the ceiling may also occur when the jet approaches the opposing wall. An adverse pressure gradient acts over a region of the ceiling (see Figure 4) and will eventually give rise to a separation.

Supply of air colder than the room air can give rise to a separation. The determinant is l_m/L. If it is less than one, the jet may separate from the ceiling before it reaches the opposite wall. As a tentative parameter for whether or not the flow in a room will be affected by the buoyancy of the jet, it has been suggested (Sandberg and Blomqvist 1994) that the ratio between the thermal length and the length of the perimeter (P) of the room, l_m/P, be used. When this ratio is much less than 1, then one can expect the flow in the room to be affected by the buoyancy of the jet.

EXPERIMENTAL RESULTS

Three-Dimensional Jet Following the Perimeter of the Room

Figure 2 (from Sandberg et al. [1991]) shows the velocities recorded at various stations along the perimeter of a room. A behavior typical for short rooms appears. When the airstream arrives at the opposite wall, the thickness of the jet increases and the jet is retarded and is deflected downward

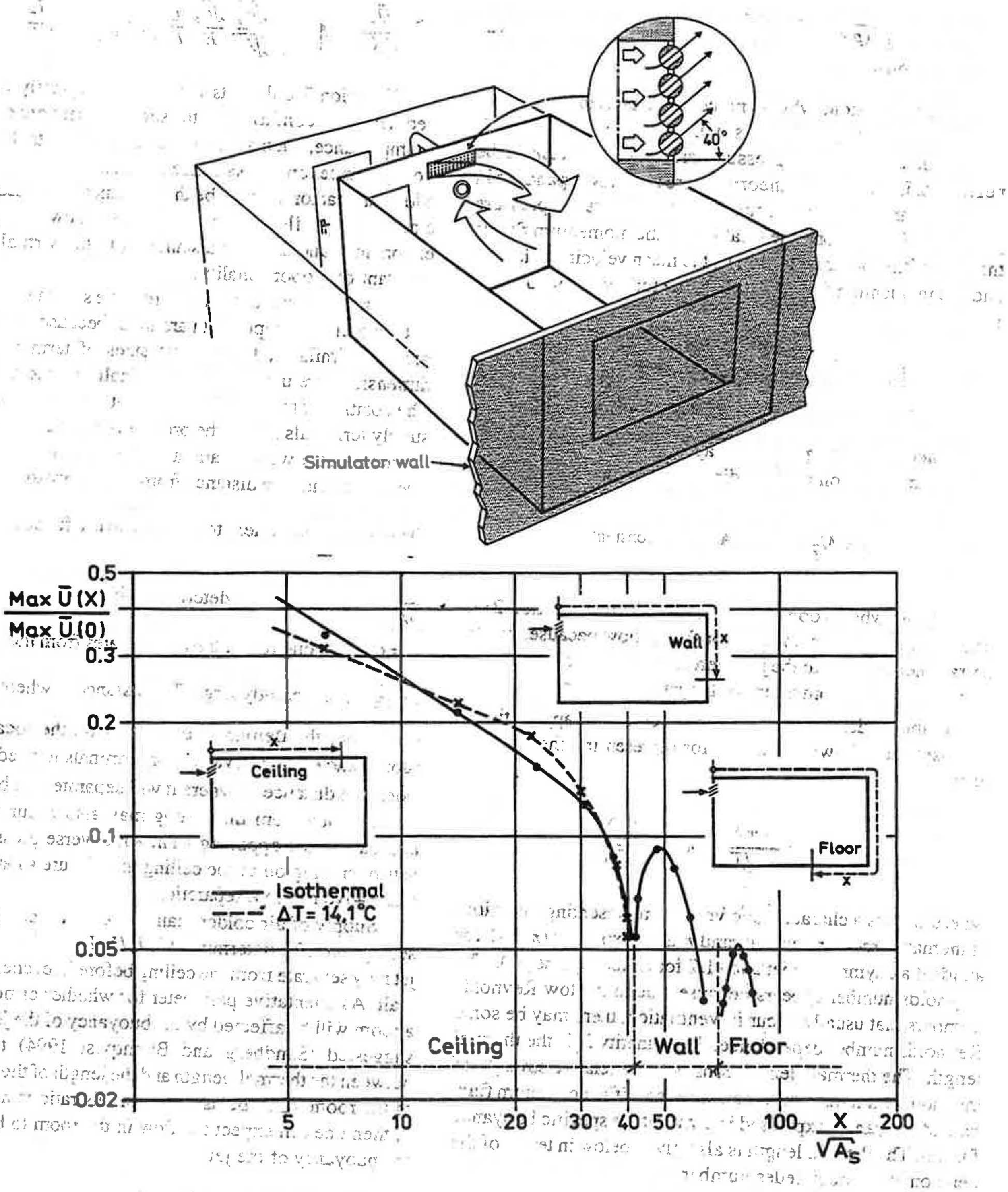

Figure 2   Maximum velocity along the perimeter of a room ($\sqrt{A_s}$ = 0.1 m).

along the wall. The jet flow is first accelerated by the higher pressure at the corner, and a maximum velocity is attained at the wall. After this point, the flow decelerates again. At the lower corner, the procedure is repeated again and the maximum velocity is attained some distance from the wall.

There are two important observations from Figure 2. The decay of the velocity under the ceiling follows the relation $x^{-0.62}$, which differs from the theoretical relationship x^{-1}. Farther downstream, the decay of the velocity is affected by the presence of the opposing wall. This is because when the jet approaches the wall, the pressure increases (see Figure 4). At the distance $x\sqrt{A(0)}$ =30, the jet starts to separate from the ceiling.

Two-Dimensional Wall Jet

All experiments reported below were carried out in slot ventilated rooms with a slot spanning the whole width of the room ($w = W$) and the terminal mounted flush to the ceiling ($y_0 = h/2$). The characteristic dimension of this terminal is equal to its height h, i.e., $\sqrt{A_s} = h$. Tests were carried out with the room configurations shown in Figure 3.

Configuration a: Both ends open
Configuration b: One end open
Configuration c: Standard room configuration

The results presented are part of a doctoral thesis (Karimipananh 1996a).

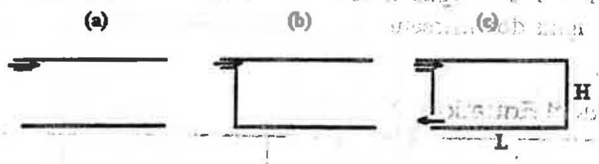

Figure 3 *Room configurations: In configuration (c), L was varied as L = 2H, 4 H/3, H, and 2 H/3, respectively.*

EXAMPLE OF PRESSURE DISTRIBUTION ALONG THE PERIMETER

Figure 4 shows an example of the static pressure along the perimeter of a room (Configuration c) with length L = H. At the beginning, the pressure decreases. However, when the jet approaches the corner, the pressure increases and the jet is exposed to an adverse pressure gradient.

EXAMPLE OF LOSSES OF MOMENTUM

Figure 5 shows the results (Karimipanah and Sandberg 1994a, 1994b) of tests conducted in a full size room (Configuration c). The momentum loss due to friction has been calculated theoretically, and the kinematic momentum fluxes have been obtained by integration of the recorded velocity field.

At first the momentum loss is due to friction only, but beyond the distance $x/h > 150$, the loss is greater than that due

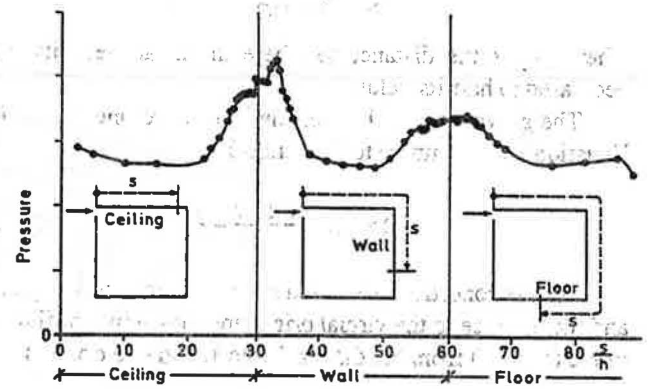

Figure 4 *Static pressure distribution along the perimeter of a room.*

to friction only. This flux may be somewhat underestimated; however, the tendency is clear. This effect can be attributed to transfer of momentum between the jet and the moving ambient. The ratio γ between the kinematic momentum flux of the mean velocity field and the total kinematic flux is about 93%.

By carrying out numerical simulations, Nielsen et al. (1996) have predicted the momentum flux M_u in a two-dimensional jet. The behavior is similar to our findings. At the beginning the losses are fairly weak because the ambient air is flowing in the same direction as the jet, but further downstream the ambient air is flowing in the opposite direction, thereby giving rise to larger losses (Nielsen 1997).

The above result shows that the jet begins to interact with room air movements when $x/h > 150$ corresponding to $x/L = 0.25$. It is of interest to compare these findings with those of Grimitlin (1970), which states that the expansion of the jet is not constrained by the room until $A_{jet} / W \times H$ amounts to about 25%.

The thickness of the jet is set to

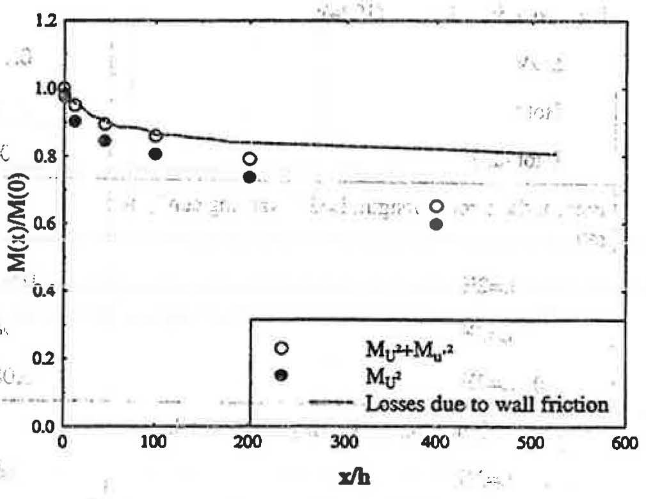

Figure 5 *Change of kinematic momentum in a jet: L = 6 m, H = 3 m, and h = 1 cm.*

$$h_{jet} = 2 \times y_{1/2} \quad (8)$$

where $y_{1/2}$ is the distance to where the mean velocity has decreased to half its value.

The growth of $y_{1/2}$ is linear and therefore one can write Equation 8 as (compare to Equation 11)

$$h_{jet} = 2 \times h \times \frac{dy_{1/2}}{dx}\left(\frac{x_0}{h} + \frac{x}{h}\right) \quad (9)$$

For the conditions shown in Figure 5, the spreading rate and the distance to the virtual origin are known in Configuration c ($L = 2H$) from the data in Table 1, and one obtains

$$\frac{h_{jet}}{h} = 0.1764\left(5.37 + \frac{x}{h}\right) \quad (10)$$

Using the Grimitlin condition, i.e., $h_{jet} / H = 0.25$, one obtains $x/h = 420$, which corresponds to $x/L = 0.7$.

SPREADING RATE AND VELOCITY DECAY

The following relations were used for curve fits of the spreading rate of the jet and the decay of the centerline velocity.

$$\frac{y_{1/2}}{h} = A_1\left(\frac{x}{h} + \frac{x_0}{h}\right)$$
$$\left(\frac{U(0)}{U_c}\right)^2 = A_u\left(\frac{x}{h} + \frac{x_0}{h}\right)^{2n} \quad (11)$$

where A_1 and A_u are constants.

The results obtained are shown in Table 1 (from Karimipanah 1996b) and are compared to those obtained by Schneider and Goldstein (1994) for an unconfined wall jet.

From Table 1 one cannot retrieve the theoretical exponent, $n = 1/2$ for the velocity decay.

CONCLUSIONS AND RECOMMENDATIONS

In summary, the behavior of an isothermal jet issued at the ceiling in a room can be described as a jet that undergoes a number of deflections at the corners it meets during its course from the supply point to the floor. When approaching the corner, it is retarded and pressure is built up. After each deflection, the jet "restarts" again. The difference between the behavior of a free jet and the behavior of a jet in a ventilated room is due to the following.

- Friction against room surfaces.
- Loss of momentum by transfer of momentum from the jet to the moving ambient.
- Buildup of an adverse pressure gradient when the jet is approaching an opposing side (room corner).
- Loss of momentum when deflected at room corners.

At first, when the jet leaves the supply device, the loss in momentum is due to friction, but after some distance, the loss becomes much greater than that by friction only. We interpret this additional loss as a loss due to exchange of momentum with the moving ambient. For a jet issued from a slot in a slot ventilated room, the loss of momentum due to exchange of momentum begins to dominate at a distance of about 150 slot heights downstream.

TABLE 1
The Calculated Constants of Equation 11

Model	$A_1 = \frac{dy_{1/2}}{dx}$	$\frac{x_0}{h}$	A_u	n	Re_h
Unconfined plane wall jet from Schneider & Goldstein (1994):					
LDV	0.077	−8.7	0.0267	0.608	
Hot film	0.082	−9.4	0.0421	0.560	14000
Pitot tube	0.074	−11.6	0.0342	0.563	
Present fixed room length, L=2H, varying configurations:					
(a) L=2H	0.0795	10.0082	0.0664	0.527	
(b) L=2H	0.0802	5.1061	0.0841	0.516	7200
(c) L=2H	0.0882	5.3745	0.1553	0.432	
Present configuration (c) varying room length:					
(c) L=2H	0.0882	5.3745	0.1553	0.432	
(c) L=4H/3	0.0888	5.7258	0.1354	0.451	7200
(c) L=2H/3	0.0880	6.1971	0.1302	0.453	

The effect of "closing in" the jet in a ventilated room is as follows:

- The jet becomes thicker, i.e., the spreading rate increases.
- The decay of the velocity does not follow a simple power law relation with a constant coefficient along the whole distance from the supply.
- When recorded velocity data are fitted to the classical jet model, consisting of a simple power law relation with one exponent, then the effect is
  — change in both the location of the virtual origin and exponent. In no case does the exponent become equal to the theoretical value -1/2 valid for a two-dimensional jet.

The main difference occurs between a free jet and a jet located in an enclosure. For a jet located in an enclosure, a change in room size does not drastically change the parameters in the classical jet model.

More than 90% of the momentum flux is transported by the mean velocity field.

For improving the precision in the prediction of the maximum velocity in the occupied zone based on properties of supply devices, the following steps are suggested:

1. A practical engineering theory should be developed, where jets in rooms are regarded as jets that undergo a number of deflections at the room corners and "restart" at each corner.
2. When testing jets one should, in addition to the determination of the length through the supply device, somehow also include the "enclosure effects" in the tests. This can, to some extent, be done at a low cost by building a mockup of a room, including the surfaces the jet strikes during its course from the supply device to the floor. The maximum velocity on the floor should be measured.

For nonisothermal jets it is suggested that the concept of thermal length be used to characterize the effect of buoyancy.

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NOMENCLATURE

dA = area differential (m^2)
A_{jet} = cross-sectional area of jet (m^2)
A_{room} = cross-sectional area of room (m^2)
Ar(0) = Archimedes number at the inlet (Ar(0) = $\frac{g' \sqrt{A_s}}{U(0)^2}$)
A_e = area of extract air terminal (m^2)
A_s = area of supply air terminal (m^2)
B = specific buoyancy flux ($B = Q(0)g'$) [m^4/s^3]
g = acceleration of gravity (m/s^2)
g' = reduced gravity, $g' = g\Delta T/T$ (m/s^2)
H = height of room (m)
h = height of supply device (m)
L = length of room (m)
l_m = thermal length (m)
M = kinematic momentum flux (N)
$M(0)$ = jet exit momentum (N)
m = specific momentum flux, $m = M/\rho$ (m^4/s^3)
n = exponent
P = length of room perimeter (m)
p = pressure (kg)
$Q(0)$ = inlet flow rate (m^3/s)
Re = Reynolds number
s = coordinate along the perimeter of the room m (m)
T = temperature (K)
$\overline{U}$ = mean value of axial velocity (m/s)
$\overline{U}_c$ = centerline velocity (m/s)
U' = fluctuating part of axial velocity (m/s)
W = width of room (m)
w = width of supply device (m)
x = coordinate in axial direction (m)
x_0 = distance to virtual origin (m)
$y_{1/2}$ = half-thickness of wall jet (m)
γ = fraction of the kinematic momentum flux due to the mean velocity field
ΔT = temperature difference (K)
ρ = density (kg/m^3)

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