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# BEHAVIOUR OF A WARM AIR JET
# IN A ROOM

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## ABSTRACT.

One of the difficulties of warm air heating is avoiding the frequent phenomena of concentration of hot air in the upper parts of a heated volume, or draughts in the occupied area.

By an analytical approach founded on the theory of jets and validated by experiments, this study proposes to supply scientific bases for a practical method of sizing supply grilles, in order to avoid these problems.

It applies essentially to concentrated axial jet grilles, where the air is emitted horizontally fairly close to the ceiling.

After having reviewed the behaviour of a free or peripheral, isothermal or anisothermal air jet, we examine the effect of concentration in a room with limited dimensions, and we devise a criterion for sizing the grille, enabling the determination of the behaviour of the stream.

# COMPORTEMENT D'UN JET D'AIR CHAUD DANS UN LOCAL

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## RESUME

L'une des difficultés du chauffage à air chaud est d'éviter les phénomènes fréquemment constatés de confinement d'air chaud dans les parties hautes du volume chauffé, ou de courants d'air dans la zone d'occupation.

La présente étude se propose, par une approche analytique fondée sur la théorie des jets et validée par l'expérimentation, de fournir les bases scientifiques d'une méthode pratique de dimensionnement des bouches de soufflage permettant d'éviter ces inconvénients.

Elle s'applique essentiellement aux bouches à jet axial concentré, émis horizontalement à faible distance du plafond.

Après avoir rappelé le comportement d'un jet d'air libre ou pariétal, isotherme ou anisotherme, on examine l'effet du confinement dans un local de dimensions limitées et l'on dégage un critère de dimensionnement de la bouche permettant de déterminer le comportement du jet.

## ISOTHERMAL JET *(figure 1)*

An isothermal jet, coming from a circular nozzle, initially forms a tapered or conical zone, at constant velocity (without mixing), followed by a diffusion zone where the transversal velocity profile takes the form of a Gaussian curve which flattens and widens linearly as it moves away from the grille. The conservation of momentum indicates that the centerline velocity decreases inversely with the distance :

$$V_a(x) = V_o \frac{d_v}{x} \quad \text{with} \quad \left[\begin{array}{l} x = \text{distance from the grille} \\ d_v = \text{length of the cone} \\ V_o = \text{initial velocity} \\ V_a = \text{centerline velocity} \end{array}\right.$$

The shorter the cone, the faster the speed decreases ; for a circular nozzle, fed under good conditions, its lenght is approximately 7 to 9 times the diameter of the nozzle ; for a grille with a grating or with multiple slots, it is substantially shorter since the presence of obstacles or a less compact aspect ratio accelerates the mixing process in the initial zone of the jet.

## WALL EFFECT. *(figure 2)*

A stream, tangent to a wall, behaves substantially like half the free jet which would be obtained by associating with it the symmetrical jet with relation to the wall. The area of the relevant dummy grille is twice, the real grille area, therefore its diameter is greater in the ratio V2. The result is that the range of the jet, for a given terminal velocity, is increased by the presence of the wall by this same ratio V2.

## EFFECT OF CONCENTRATION OR CONFINEMENT.

Observations made in a climatic chamber have shown that, if the range is sufficient, an isothermal air jet insufflated along the ceiling of a room, extends along the wall opposite, then along the floor, with a speed decrease law which substantially extends that of the first horizontal trajectory *(figure 3)*.

This phenomenon , which expresses the conservation of momentum during successive direction changes, appears as an air circulation along the walls, all around the room, which is a powerful homogenizing factor.

Nevertheless, with hot air, the phenomenon is opposed by the upward force which tends to block the descent of the stream. We can then observe a completely different behaviour where a circulation of hot air occurs in a zone close to the ceiling, a zone which has a very low rate of mixing with the rest of the air volume which remains practically stagnant. This situation creates a high vertical gradient of temperature, a source of discomfort and an energy waste *(figure 4)*.

## CONDITIONS FOR EFFICIENT MIXING.

To avoid the latter situation, we need to identify a criterion, depending upon the parameters defining the stream and the room, which will enable us to predict how the stream will behave, i.e. peripheral circulation, or stagnation at the upper part, and naturally, intermediate situations are possible. The form of this criterion must result from theoretical considerations, but the limit value to be employed should preferably be determined based upon experimentation.

Our approach is as follows.

If we admit, after its impact on the wall opposite the grille, that the stream begins by moving downward, we can calculate the limit drop distance, determined by the opposing effet of buoyancy, and we can admit that the phenomenon of hot air confinement at the upper part will become more pronounced as the drop distance becomes lesser with relation to the height of the room.

The drop distance is calculated by assuming that the descending part of the stream initially possesse the same characteristics (heat flux and momentum) as the horizontal stream at the end of its travel, by applying to it the velocity law of a descending hot air jet.

In comparison with the law of the isothermal jet, this law contains a supplementary braking term due to the buoyant forces which diminish the momentum, and a limit drop distance appears where the velocity is cancelled *(figure 5)*.

The calculation shows that this limit drop distance is substantially proportional to the expression $\frac{V_o^2 D}{t_o L}$, in which :

- $V_o$ and $t_o$ are the initial values of the velocity and of the temperature difference,
- D and L are the diameter of the grille and the lengh of the room.

For the mix to be efficient, it is necessary that the drop distance not be too short in comparison with height H of the room, which can result in a condition affecting the initial velocity and having the following form :

$$\boxed{V_o > k \frac{t_o HL^{1/2}}{A^{1/4}}}$$

A is the section of the grille and k may depend upon the type of grille.

**EXPERIMENTAL VALIDATION.**

Tests performed in a climatic chamber at the CSTB have enabled us to assess the validity of this criterion and to establish the desirable value. These tests involved "off the shelf" grilles with grating or slots, with sections varying from 20 $cm^2$ to 125 $cm^2$, with incoming air velocities from 2,2 to 7 m/s and temperature differences from 7°C to 34°C.

Dimensions of the chamber : 3,6 m X 3,6 m, height 2,5 m.

Figure 6 shows the correlation which exists between the expression:

$$\frac{V_o A^{1/4}}{t_o HL^{1/2}},$$

representing criterion k, and the air temperature difference between the top of the room (average value at 10 cm from the ceiling) and the center of the room.

The ambient conditions in these various tests were analyzed with the aid of the UCRES comfort profile, which expresses, for 5 criteria, the effect of the intensity and of the space domain frequency of the discomfort created throughout the occupied zone, by means of a note N, varying from 0 to ± 5.

$$N = 4,15 \log (1 + 3 f_1 + 15 f_2),$$

$f_1$ and $f_2$ being respectively the fraction of the space where the ambience is "slightly" or clearly" uncomfortable.

The 5 "bother" criteria are : Horizontal <u>U</u>niformity,
Draughts ("<u>C</u>ourants d'air")
Disymmetrical <u>R</u>adiation,
Thermal difference between head and feet ("<u>E</u>cart tête-pieds")
Floor temperature ("Temperature du <u>S</u>ol").

An analysis of the UCRES profile and of the vertical temperature profile for 4 tests *(figure 7)* situates the acceptable limit, in terms of head-feet difference and warm draughts (at head level) under the conditions of test number 6, which correspond to a difference of 3,5°C between the zone near the ceiling and the center, along with a value of approximately 0,11 of the k coefficient for grilles which are similar to those which have been tested, that is, grilles with grating or slots, producing a non-divergent stream.

## SIZING THE GRILLES.

For a given value of input air temperature and for a given air flow, the hot air non confinement requirement leads to setting an upper limit for the grille section.

On the other hand, an excessively fast speed can create bothersome draughts, particularly at foot level, near the wall, opposite the grille. This hazard is avoided by limiting the range of the isothermal peripheral jet (equal to 1,4 times the corresponding free jet range, defined for a terminal velocity of 0,25 m/s) to the sum L + H of the length and height of the room.

This double condition leads to the chart in figure 8, which can be used to immediately obtain the authorized grille section range, given a particular necessary thermal power, input air temperature difference and room length (this chart is prepared for a ceiling height of 2,5 m).

These two conditions are only compatible if the power is less than the following value :

$$\boxed{P_{max} = 78 \frac{(L + H)^3}{L\ H}}$$

Beyond that, it is necessary to install at least two grilles.

Another limitation is related to the acoustic requirement, which, in a dwellinunit, leads to limiting the air input velocity to a value of approximately 6,5 m/s. This requirement leads to limiting the input air temperature difference to the following value :

$$\boxed{t_0\ max = 8 \frac{P^{1/3}}{L^2}}$$

## CONCLUSION.

This sizing method results from research conducted at the CSTB, combining an analytical approach with experimentation. Developed under a contract between the GDF (French National Gas Utility) and the CSTB, concerning gas heating systems with forced warm air, the method was implemented in a group of 25 experimental homes at La Valbonne, where the results generally confirmed the predictions.

These encouraging results however concern only one particular air diffusion method, and an extension of this research would be useful so that the principles derived might be applied to other insufflation techniques.

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