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# Experimental study of thermal stratification in ventilated confined spaces

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## Abstract

Within the displacement ventilation (DV) field, this paper presents an experimental study of thermal stratification in a ventilated room in which there is a heat source. The ventilation system maintains plume development up to a limiting height, above which the air stream is mixed. Temperature stratification arises within the test room. Its interface is of significant thickness and its position is identified by that of the maximum standard deviation of temperature fluctuations. The change in the height of this interface is studied under different experimental conditions. Results confirm the laws already obtained for zones close to and far away from the source and they also allow a law governing the transition between these two zones to be proposed.


*Keywords:* Displacement ventilation; Natural convection; Thermal stratification; Thermal plume

## 1. Introduction

A heat source placed in a room generates a thermal plume by natural convection. As it develops, this plume conveys an ambient air flow, which increases as it rises within the room. The room may be ventilated by supplying a low velocity make-up air flow at low level and extracting the same flow at high level. Under certain conditions affecting the dynamic parameters for the envisaged tests, the airflow can include recirculation zones in the upper part of the enclosed space. In these cases, vertical temperature stratification is created. Two main zones thus appear in the steady state: a lower zone fed by make-up air and an upper zone featuring warm recirculated air. A thermocline separates these two zones and its position within the room corresponds to the level at which the plume flow rate equals the ventilation flow rate.

If the source of heat is also a source of pollutants, these remain confined not only within the plume, but also within the zone located above the thermocline. The problem of sizing a displacement ventilation installation (DV) involves determining from the source's characteristics (convected power and size) the flow rate to be implemented to ensure that the thermocline is located above the occupied zone.

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**Nomenclature**

| | |
|---|---|
| $C$ | fluorescent tracer concentration ($\mathrm{mol\,m^{-3}}$) |
| $C_\mathrm{p}$ | specific heat of air ($\mathrm{J\,kg^{-1}\,K^{-1}}$) |
| $D_\mathrm{s}$ | thermal source diameter (m) |
| $g$ | acceleration due to gravity ($\mathrm{m\,s^{-2}}$) |
| $K$ | constant ($\mathrm{m^{-4/5}\,W^{1/5}\,s^{3/5}}$) |
| $P_\mathrm{c}$ | source convected power (W) |
| $Pr$ | Prandtl number |
| $Q$ | entrained plume flow rate ($\mathrm{m^3\,s^{-1}}$) |
| $Q_\mathrm{v}$ | ventilation flow rate ($\mathrm{m^3\,s^{-1}}$) |
| $Ra$ | Rayleigh number |
| $T$ | temperature (°C) |
| $X$ | dimensionless number |
| $z$ | height (m) |
| $Z_\mathrm{c}$ | ceiling height (m) |
| $z_\mathrm{i}$ | interface height (m) |
| $z_\mathrm{v}$ | position of plume virtual origin (m) |
| *Greek symbols* | |
| $\beta$ | coefficient of thermal expansion ($\mathrm{K^{-1}}$) |
| $\nu$ | kinematic viscosity ($\mathrm{m^2\,s^{-1}}$) |
| $\sigma$ | standard deviation (°C) |
| $\rho$ | density ($\mathrm{kg\,m^{-3}}$) |
| *Suffixes* | |
| a | ambient |
| s | source level |

Extensive research has been undertaken to characterise plume development in an infinite space [1,2]. These studies have shown that a plume develops essentially in two stages: the plume development zone and the self similar zone featuring a fully developed plume. In the second zone, well documented in scientific literature, the plume can be described from relationships involving just two parameters, namely the power convected by, and the distance from, the source. On the other hand, very few results are available for describing the development region close to the source. However, in industrial ventilation applications, the room occupied zone corresponds to a height at which the plume is rarely fully developed. Laws permitting detailed description of the plume and its flow rate in this zone close to the source must be established to permit proper sizing of DV systems.

In the present study, we consider the plume created by a circular heat source, developing in a ventilated confined space. Two laws governing the change in thermocline height with respect to various parameters (ventilation flow rate, source convective power and diameter) have been proposed by Auban [3,4]. These laws were obtained by applying an experimental approach based on a hydraulic model. Solutal simulation-based observations were conducted using a Rayleigh similarity lying on the analogy between thermal and mass transfer. Far away from the source, the first law is equivalent to the law governing changes in a fully developed plume. Close to the source, the second empirically established law involves an additional geometrical parameter: the source diameter. The main aim of this research involves studying these laws and their validation in ventilation situations.

In particular, for the zone far away from the source, our experimental results are compared to those obtained from conventional formulas used for the sizing of DV systems. These formulas are usually based on the hypothesis that at the thermocline level the entrained flow rate of the plume equals the ventilation flow rate [5,6]. The law describing the entrained flow for a steady-state plume is written in the form [7,8]

$$Q = KP_\mathrm{c}^{1/3}(z - z_\mathrm{v})^{5/3} \tag{1}$$

where $Q$ is the entrained plume flow rate, $P$ is the convective heat power of the source, $z - z_\mathrm{v}$ is the distance from the virtual origin of the plume and $K$ is a constant which for standard ventilation applications equals 0.005 (Skaret model [9]).

## 2. Experimental facilities

### 2.1. Test room

The test room (Fig. 1) provided a floor area of $4.8 \times 4.2\,\mathrm{m}^2$ and a height of 5.6 m. It was contained within an outer enclosure, whose overall height was 7.4 m. The lower and upper parts of the test room were bounded by a perforated floor and ceiling respectively. Ventilation was ensured by four flexible fabric blowing ducts located beneath the test room floor. Air extraction from the upper part of the test room was ensured from above the perforated ceiling by three ducts also made of flexible fabric. The air treatment unit included cooling and heating batteries and a fan. A control device allowed the ventilation flow to be set to any value between 2000 and 10,000 $\mathrm{m^3\,h^{-1}}$. Blowing temperature could also be selected within an 18–25 °C range. The cooling battery was designed to allow all heat sources of power less than 18 kW to be studied.

### 2.2. Heat sources

Heat sources used were made up of two 5 mm thick, horizontal copper disks of different diameters (0.9 and

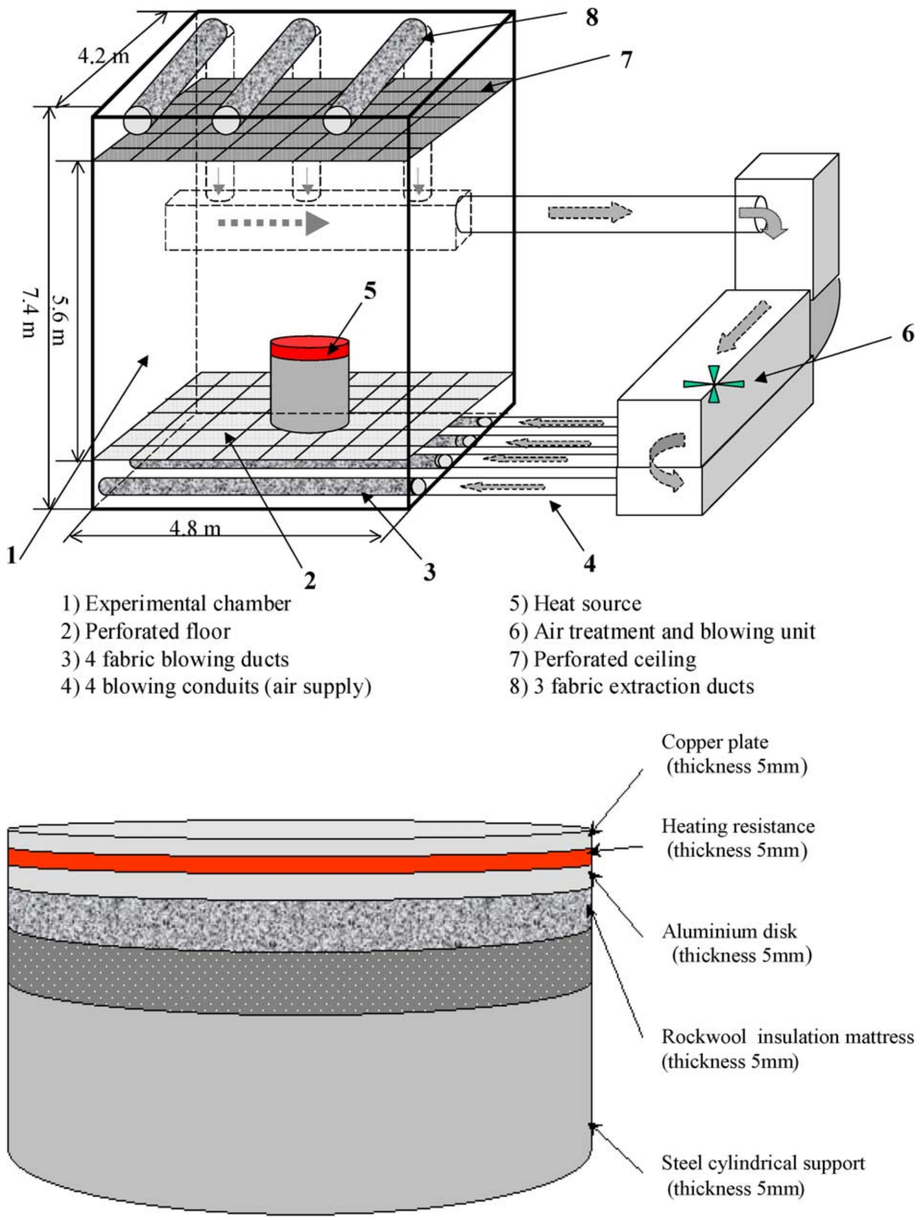


Fig. 1. Ventilation test room and heat source.

1.54 m) heated to approximately 200 °C. Each disk was placed on a heating resistance integrated into an aluminium support. This device was placed on a 100 mm thick rockwool insulating mattress. A sheet-steel cylinder was used to support the described assembly (Fig. 1).

### 2.3. Measuring devices

Measurements were taken using a battery of 16 type K thermocouples featuring 0.14 mm diameter wires. A precision weld formed the hot junction at the end of each thermocouple, which was connected to the measuring unit by a cable suited to the thermocouple characteristics. The cold weld was integrated inside the measuring unit's compensation module. This arrangement ensured a thermocouple response time of the order of 1 s. A sensitivity of the order of 0.1 °C could be expected for this type of thermocouple.

Thermocouples used were calibrated on a calibration bench before being mounted on the rule, which

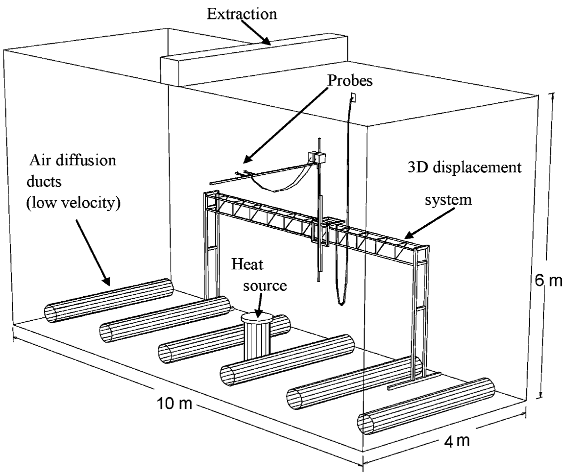


Fig. 2. Diagram of climatic chamber (FIOH, Finland).

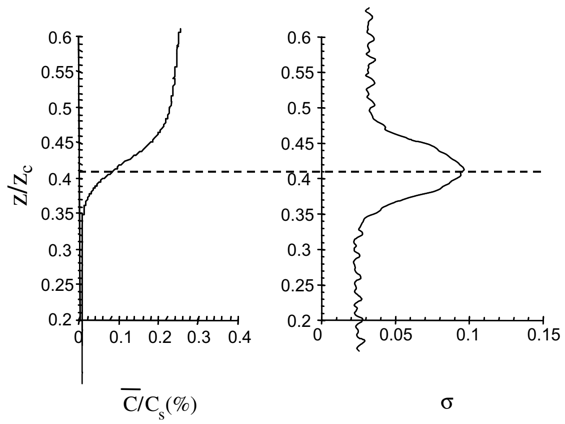


Fig. 3. Vertical profiles of mean concentration and fluctuation standard deviation obtained in hydraulic simulations ([4]).

supported them. Measuring accuracy was evaluated at ±0.3 °C.

### 2.4. Auxiliary installation

Prior to building the INRS test room, ventilation tests were conducted in a climatic chamber ($10 \times 4 \times 6\ m^3$) (Fig. 2) installed at the FIOH (Finnish Institute of Occupational Health, Finland) laboratories. Two 0.6 m and 1.0 m diameter aluminium disks were used as heat sources, each disk was placed on a heating element with an insulated bottom face and this assembly was mounted on a 1.0 m high cylinder. Tracer gas ($SF_6$) was injected at a constant rate at the heat source. The ventilation flow was distributed by six 400 mm diameter perforated ducts located 5 cm above floor level. Air extraction was ensured by a perforated plate ($0.4 \times 2\ m^2$) mounted in the centre of the ceiling. In this experimental set-up, the tracer gas concentration field could be reproduced point by point using a photoacoustic probe. Local temperature was measured by a thermistor mounted, along with the photoacoustic probe, on a 3D displacement system.

## 3. Interface location

A number of authors have proposed definitions based on mean temperature or tracer gas concentration profiles for locating the thermocline. According to Mierzwinski et al. [10], thermocline height corresponds to the level at which the temperature difference with respect to the blown air reaches 30% of the temperature difference measured at the ceiling. Trzeciakiewicz et al. [11] retain an interface height corresponding to the level at which the tracer gas concentration reaches 50% of the concentration injected at the heat source. Both Xing and Awbi [12,13] and Stymne et al. [14] consider that the interface is at the altitude at which the wall temperature is locally equal to the air temperature. Alternatively, Auban [3,4] demonstrates that the interface can be located by studying statistically fluctuations in fluorescent tracer concentration measured at each point. The latter analysis is presented in Fig. 3. The interface position can be located by finding the position of the concentration maximum gradient or, more accurately, using the maximum standard deviation of fluctuations in concentration. This can be explained by the fact that the interface zone corresponds to a mixing zone between structures coming from higher or lower thermocline levels.

In a previous work, it has been shown that the mean temperature profile does not reveal as clear a stratification phenomenon as the results obtained with tracer gas (Fig. 4) [15]. This could be due to radiation, which does not affect tracer gas behaviour. Analysis of the standard deviation of fluctuations reveals a very pronounced peak locating the interface position as in the case of hydraulic simulation.

## 4. Test conditions

The different experimental conditions used to study changes in thermocline height are summarised below. Some of these tests were conducted at INRS, whilst others were conducted in the FIOH ventilation test room described in Section 2.4. Table 1 presents the conditions associated with the different heat sources used in the two facilities.

Under all these test conditions, the ventilation flow rate varied between 800 and 4000 $m^3\,h^{-1}$ for INRS con-

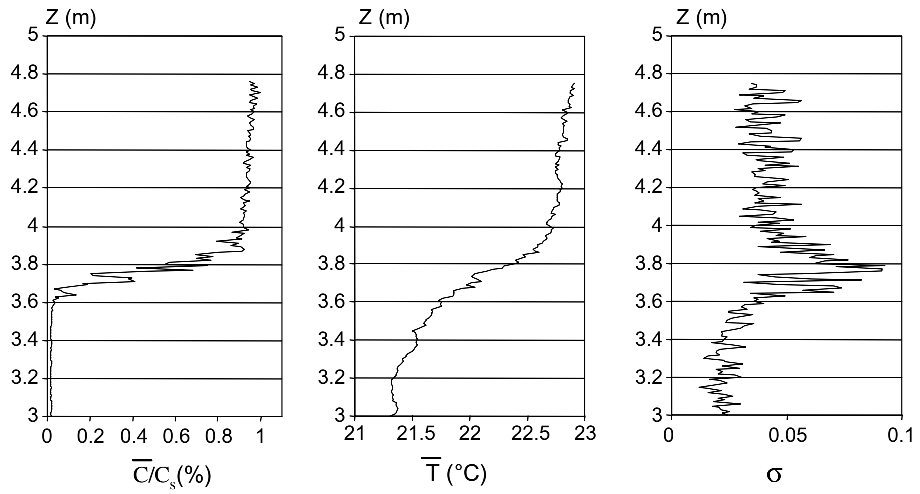


Fig. 4. Vertical profiles of normalised tracer gas mean concentration, mean temperature and temperature fluctuation standard deviation obtained in the FIOH ventilation chamber [15].

Table 1
Characteristics of heat sources used

| INRS | | FIOH | |
|---|---|---|---|
| Diameter (m) | Temperature (°C) | Diameter (m) | Temperature (°C) |
| $D_{s1} = 0.9$ m | $T_{s1} = 200$ °C<br>$T_{s2} = 250$ °C | $D_{s3} = 0.6$ m | $T_{s1} = 200$ °C |
| $D_{s2} = 1.54$ m | $T_{s1} = 200$ °C<br>$T_{s3} = 230$ °C | $D_{s4} = 1.0$ m | $T_{s1} = 200$ °C |

figurations and between 162 and 1267 $m^3 h^{-1}$ for the FIOH configuration.

## 5. Experimental procedure

To locate the thermocline, 16 type K thermocouples were placed on a vertical axis, 2 m from the centre of the heat source (Fig. 5) and arranged as follows:

The first thermocouple was positioned at source level, giving the air blowing temperature at this level.

The next 14 thermocouples were positioned at 10 cm intervals along a moving vertical rule, covering the stratification zone.

The last thermocouple was fixed at ceiling level, indicating the air recovery temperature.

Ventilation flow and temperature set-points were fixed. Temperature readings were taken after awaiting establishment of the thermal state (approximately 3 h). These readings were then taken during 2 h at a sampling frequency of 10 Hz for each probe.

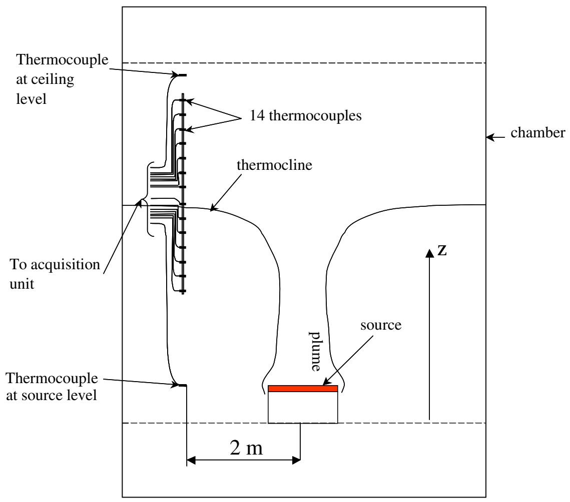


Fig. 5. Thermocouple arrangement for thermocline characterisation.

## 6. Experimental results

Fig. 6 shows the change in stratification height $z_i$ with respect to ventilation flow rate for the different tests. In this figure, it is obvious that the stratification height increases with the flow rate for a given source at a fixed surface temperature. This observation is entirely consistent with the predicted stratification at a height $z$, at which the plume and ventilation flow rates are equal. Similarly, it should be noted that, for the same flow rate and source diameter, the thermocline height reduces

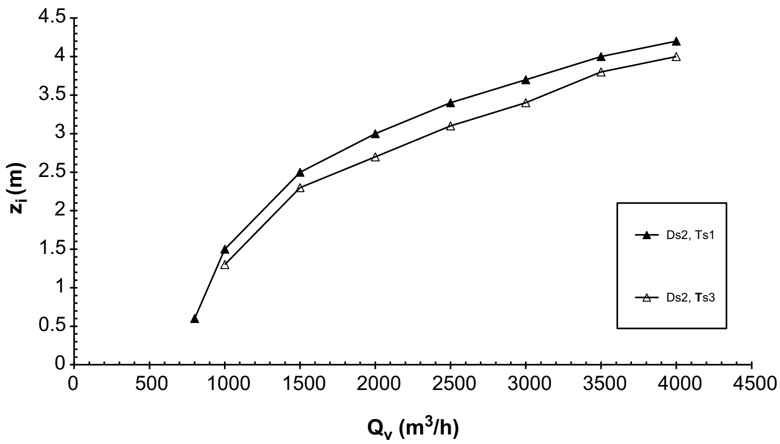


Fig. 6. Stratification height versus ventilation flow rate (INRS).

when the source temperature increases, which moreover corresponds to an increase in convected power.

## 7. Comparison with literature-based results

We used the formulae proposed by Auban [3,4] and that used by Skåret [9] to test our experimental data.

The formulae retained by Auban [3,4] can be expressed as:

$$\left(\frac{z_{\mathrm{i}}}{D_{\mathrm{s}}}\right)^{2/3} \cong 5.5X \quad \text{in the zone close to the source} \tag{2}$$

$$\left(\frac{z_{\mathrm{i}}-z_{\mathrm{v}}}{D_{\mathrm{s}}}\right)^{5/3} \cong 19.25X \quad \text{in the zone far from the source} \tag{3}$$

where $z_{\mathrm{v}}$ is the position of the plume virtual origin, which can be experimentally determined.

These formulae are based on the following definition of the dimensionless variable $X$:

$$X=\frac{Q_{\mathrm{v}}}{D_{\mathrm{s}}v}\left[\frac{Pr^{2}}{Ra^{4/3}}\right]^{1/3} \tag{4a}$$

This coefficient has been established assuming that the Nusselt number, characterizing exchange at the source, is related to the Rayleigh number by the law $Nu=0.15Ra^{1/3}$ which needs $2\times10^{7}<Ra<3\times10^{10}$(a typical value for the experimentations presented here being $Ra=1.9\times10^{10}$).

Preferring an expression in terms of the source convective power, this variable $X$ is again expressed as

$$X=0.5\left(\frac{\rho C_{\mathrm{p}}}{g\beta}\right)^{1/3}\frac{Q_{\mathrm{v}}}{D_{\mathrm{s}}^{5/3}P_{\mathrm{c}}^{1/3}} \tag{4b}$$

with a source at a temperature of approximately 200 °C in ambient air at 20 °C, this would give

$$X=16\frac{Q_{\mathrm{v}}}{D_{\mathrm{s}}^{5/3}P_{\mathrm{c}}^{1/3}} \tag{4c}$$

The relation derived from the one proposed by Skåret [9] (Eq. (1)) can be expressed as:

$$z_{\mathrm{i}}-z_{\mathrm{v}}=24.02P_{\mathrm{c}}^{-1/5}Q_{\mathrm{v}}^{3/5} \tag{5a}$$

$$\text{i.e.}\quad \left(\frac{z_{\mathrm{i}}-z_{\mathrm{v}}}{D_{\mathrm{s}}}\right)^{5/3} \cong 200\frac{Q_{\mathrm{v}}}{D_{\mathrm{s}}^{5/3}P_{\mathrm{c}}^{1/3}} \tag{5b}$$

Table 2
Summary of experimental conditions (physical parameters and dimensionless numbers calculated at film temperature)

| | Source diameter $D_{\mathrm{s}}$ (m) | Source temperature $T_{\mathrm{s}}$ (°C) | Ambient temperature $T_{\mathrm{a}}$ (°C) | Rayleigh number $Ra$ | Convected power $P_{\mathrm{c}}$ (kW) | Virtual origin $z_{\mathrm{v}}$ (m) | $z_{\mathrm{v}}/D_{\mathrm{s}}$ |
|---|---|---|---|---|---|---|---|
| INRS | 0.9 | 200 | 20 | 3.8E+9 | 1.0 | 1.2 | 1.3 |
| | 0.9 | 250 | 20 | 3.7E+9 | 1.3 | 1.2 | 1.3 |
| | 1.54 | 200 | 20 | 19.1E+9 | 2.8 | 2.2 | 1.5 |
| | 1.54 | 230 | 20 | 18.7E+9 | 3.4 | 2.2 | 1.5 |
| FIOH | 0.6 | 200 | 20 | 1.1E+9 | 0.4 | 1.3 | 2.1 |
| | 1 | 200 | 20 | 5.2E+9 | 1.2 | 2.2 | 2.2 |

Table 3
Comparison of stratification heights measured and calculated for different ventilation flow rates (Auban's [3,4] and Skaret's [9] laws)

| Experimental parameters | Ventilation flow rate | Dimensionless variable | Zone close to source | | Zone far from source[a] | | |
|---|---|---|---|---|---|---|---|
| | | | Auban's law | Measurements | Auban's law | Skåret's law | Measurements |
| | $Q_v$ (m$^3$ s$^{-1}$) | $X = 16\frac{Q_v}{D_s^{5/3}P_c^{1/3}}$ | $\frac{z_i}{D_s} = (5.5X)^{3/2}$ | $\frac{z_{exp}}{D_s}$ | $\frac{z_i - z_v}{D_s} = (19.25X)^{3/5}$ | $\frac{z_i - z_v}{D_s} \cong (12.5X)^{3/5}$ | $\frac{z_{exp} - z_v}{D_s}$ |
| $D_{s1}$, $T_{s1}$ (INRS) | 0.222 | 0.43 | 3.7 | 3.3 | 3.6 | 2.8 | 4.7 |
| $D_{s1}$, $T_{s2}$ (INRS) | 0.222 | 0.39 | 3.2 | 3.0 | 3.4 | 2.6 | 4.4 |
| | 0.278 | 0.49 | 4.4 | 3.7 | 3.8 | 3 | 5.1 |
| $D_{s2}$, $T_{s1}$ (INRS) | 0.222 | 0.12 | 0.6 | 0.4 | 1.7 | 1.3 | 1.9 |
| | 0.278 | 0.15 | 0.8 | 1 | 1.9 | 1.5 | 2.4 |
| | 0.417 | 0.23 | 1.4 | 1.6 | 2.4 | 1.9 | 3.1 |
| | 0.556 | 0.31 | 2.2 | 1.9 | 2.9 | 2.3 | 3.4 |
| | 0.694 | 0.38 | 3.1 | 2.2 | 3.3 | 2.6 | 3.6 |
| | 0.833 | 0.46 | 4.1 | 2.4 | 3.7 | 2.9 | 3.8 |
| | 0.972 | 0.54 | 5.1 | 2.6 | 4.1 | 3.1 | 4 |
| | 1.111 | 0.62 | 6.2 | 2.7 | 4.4 | 3.4 | 4.2 |
| $D_{s2}$, $T_{s3}$ (INRS) | 0.278 | 0.15 | 0.7 | 0.8 | 1.9 | 1.4 | 2.3 |
| | 0.417 | 0.22 | 1.3 | 1.5 | 2.4 | 1.8 | 2.9 |
| | 0.556 | 0.29 | 2.0 | 1.8 | 2.8 | 2.2 | 3.2 |
| | 0.694 | 0.36 | 2.8 | 2.0 | 3.2 | 2.5 | 3.4 |
| | 0.833 | 0.44 | 3.7 | 2.2 | 3.6 | 2.8 | 3.6 |
| | 0.972 | 0.51 | 4.7 | 2.5 | 3.9 | 3 | 3.9 |
| | 1.111 | 0.58 | 5.7 | 2.6 | 4.3 | 3.3 | 4 |
| $D_{s3}$, $T_{s1}$ (FIOH) | 0.046 | 0.23 | 1.4 | 0.8 | 2.5 | 1.9 | 2.9 |
| | 0.053 | 0.27 | 1.8 | 1.0 | 2.7 | 2.1 | 3.1 |
| | 0.062 | 0.31 | 2.3 | 1.3 | 2.9 | 2.3 | 3.4 |
| | 0.080 | 0.40 | 3.3 | 2.2 | 3.4 | 2.6 | 4.2 |
| | 0.100 | 0.50 | 4.6 | 2.5 | 3.9 | 3.0 | 4.6 |
| | 0.120 | 0.60 | 6.1 | 2.8 | 4.4 | 3.4 | 4.9 |
| | 0.145 | 0.73 | 8.1 | 3.3 | 4.9 | 3.8 | 5.4 |
| | 0.196 | 0.99 | 12.7 | 4.0 | 5.9 | 4.5 | 6.1 |
| | 0.253 | 1.27 | 18.6 | 4.8 | 6.8 | 5.3 | 6.9 |
| | 0.280 | 1.41 | 21.6 | 5.5 | 7.2 | 5.6 | 7.6 |
| $D_{s4}$, $T_{s1}$ (FIOH) | 0.098 | 0.15 | 0.7 | 0.6 | 1.9 | 1.5 | 2.8 |
| | 0.105 | 0.16 | 0.8 | 0.8 | 2.0 | 1.5 | 3.0 |
| | 0.118 | 0.18 | 1.0 | 0.9 | 2.1 | 1.6 | 3.1 |
| | 0.137 | 0.21 | 1.2 | 1.0 | 2.3 | 1.8 | 3.2 |
| | 0.157 | 0.24 | 1.5 | 1.2 | 2.5 | 1.9 | 3.4 |
| | 0.200 | 0.31 | 2.2 | 1.5 | 2.9 | 2.2 | 3.7 |
| | 0.247 | 0.38 | 3.0 | 2.0 | 3.3 | 2.5 | 4.2 |
| | 0.352 | 0.54 | 5.1 | 2.8 | 4.1 | 3.2 | 5.0 |

[a] In the zone far from the source, the virtual origin position is as shown in Table 2.

i.e. $$\left(\frac{z_\mathrm{i}-z_\mathrm{v}}{D_\mathrm{s}}\right)^{5/3} \cong 12.5X \tag{5c}$$

To use these relations in our experimental conditions, we must know the amount the power convected by the source or the Rayleigh associated with this transfer.

Values of $Ra$ and $P_\mathrm{c}$ retained for each experiment are therefore recorded in Table 2. This table also recalls the position of the virtual origin determined experimentally for each source, in the case a developed plume without stratification.

Table 3 presents stratification heights calculated for different sources and ventilation flow rates using the formulae proposed by Auban [3,4] and Skåret [9]. Results of experimental measurements are given in the same table. Fig. 7 illustrates this comparison, retaining Auban's proposal [3,4] for the zone close to the source. Fig. 8 compares the experimental data with Auban's [3,4] and Skåret's [9] proposals for the zone far from the source.

We also recorded the experimental results obtained by Auban [3,4] and these are shown in Figs. 7 and 8.

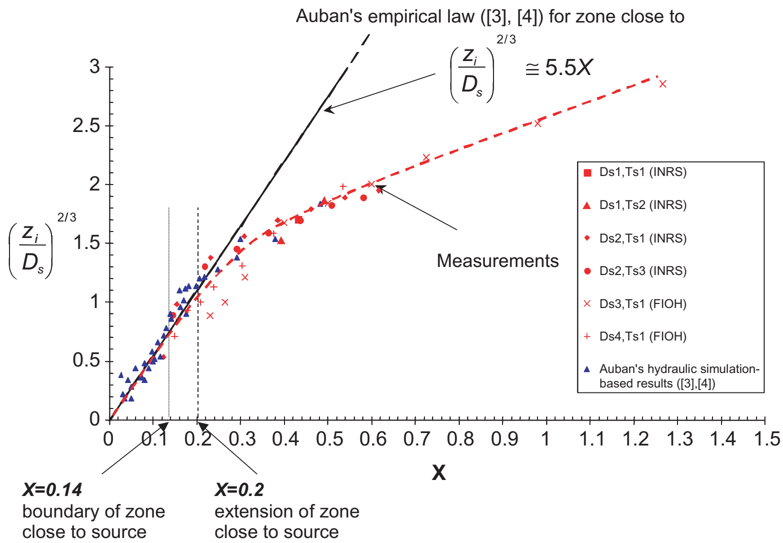


Fig. 7. Experimental and empirical stratification heights for zone close to the source.

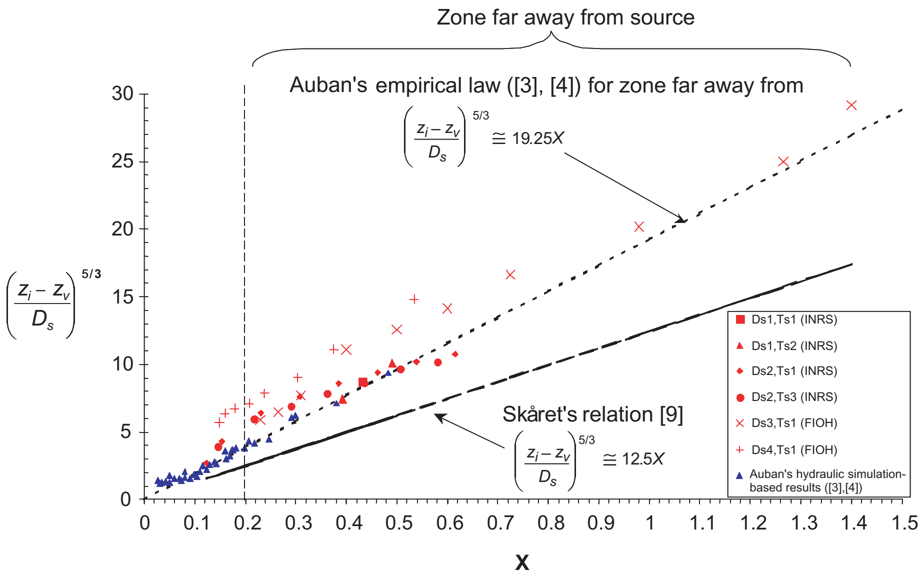


Fig. 8. Experimental and empirical stratification heights for zone far away from source.

The boundary between the zones close and far away from the source defined in Auban's work [3,4] occurs when $X = 0.14$. Given the INRS operating conditions, the ventilation flow rate could not be reduced to less than $800\ \mathrm{m^3\,h^{-1}}$ and the source temperature could not be increased to more than 230 °C, corresponding to a value of $X = 0.12$. Within our experimental framework, investigations in the zone close to the source were therefore somewhat limited. However, we note in Fig. 7 that our results in the zone close to the source agree closely with both those of Auban [3,4] and those obtained in Finland. It would therefore seem that the effects induced by radiation exchanges do not alter the determined thermocline height. From his experiments, Nielsen [16] deduced that, whilst source radiative power influences thermocline thickness, it does not affect thermocline height. Our observations support this prediction: stratification thicknesses measured by Auban [3,4] at 1 and 2 diameters above the source are thus $0.08$–$0.15D_s$. Based on our observations, in which radiation cannot be neglected, thermocline thickness is of the order of 1–$1.5D_s$, i.e. 10 times as great.

Stratification heights recorded in Fig. 7 concern experiments in which radiation plays very different roles. However, up to at least $X = 0.2$, stratification heights do indeed obey Auban's proposed law [3,4] in the zone close to the source. This law could therefore be extended to what is generally termed the intermediate zone.

Grouping together of experimental points on the same curve in the interval $0.2 < X < 1.0$ is not observed in Fig. 8, concerning the zone far away from the source. We must therefore consider that source dimensions continue to affect plume development in this region. If we adhere to the dimensional analysis and extend Auban's proposed law for the zone close to the source, it would seem that all points can be represented by the following relation for $X > 0.2$ and up to at least 4 diameters from the source [19]:

$$\left(\frac{z_i}{D_s}\right)^{4/3} \cong 6.8X$$

This law is intermediate between the two laws established by Auban [3,4]; the first a 2/3rd power law indicating that $z_i$ is highly dependent on $D_s$, and the second a 5/3rd power law indicating independence on this diameter (when using the definition of the dimensionless variable $X$, Eq. (4c). The notion of virtual origin is somewhat confused in this zone, up to 3 or 4 diameters from the source. Some authors have suggested altering the value to be retained for this position when describing plume development involving stratification in confined spaces. Fig. 9 demonstrates the appropriateness of the law proposed for this transition zone with respect to all our experimental results.

Our experimental conditions do not allow distances greater than $3D_s$ to be reached. The experiments conducted in Finland for distances up to $6D_s$ still obey this 4/3rd power law. However, it should be noted that our predictions cover the law proposed by Auban [3,4] at this distance (Fig. 8). On the other hand, the experimental observations are further away from Skåret's predictions [9].

We may observe here that the two relations proposed by Auban [3,4] and Skåret [9] are derived from the same law based on dimensional analysis and given by

$$z_i - z_v = KP_c^{-1/5}Q_v^{3/5}$$

where $K$ is a constant.

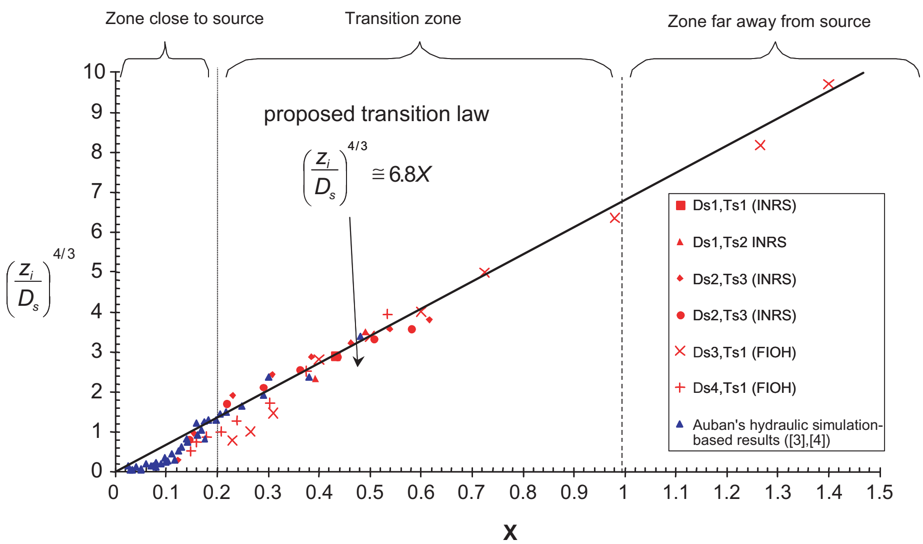


Fig. 9. Experimental and empirical stratification heights for intermediate zone.

In Skåret's case [9], this constant is equal to 24 and in Auban's case [3,4], it is equal to 31. The difference between these two constants probably depends on experimental conditions and perhaps on the criterion retained for defining the thermocline.

It should be recalled that Skåret's law [9], confirmed by Kofoed and Nielsen [17], is based on real velocity and temperature measurements. This law predicts the plume flow rate at each height far away from the source in an infinite space. The law proposed by Auban [3,4] is based on measuring a height at which mixing between cool and recirculated zones corresponds to the maximum standard deviation of fluctuations in the observed variable.

In the case of very thin stratification, we can predict that this will occur when the plume and ventilation flow rates are equal. If stratification affects a layer of significant thickness, it is difficult to say exactly at what level this equality occurs within the layer. Fig. 10 shows vertical temperature profiles measured outside the plume for several ventilation flow rates. In the same figure, we indicate the stratification height derived from Skåret's

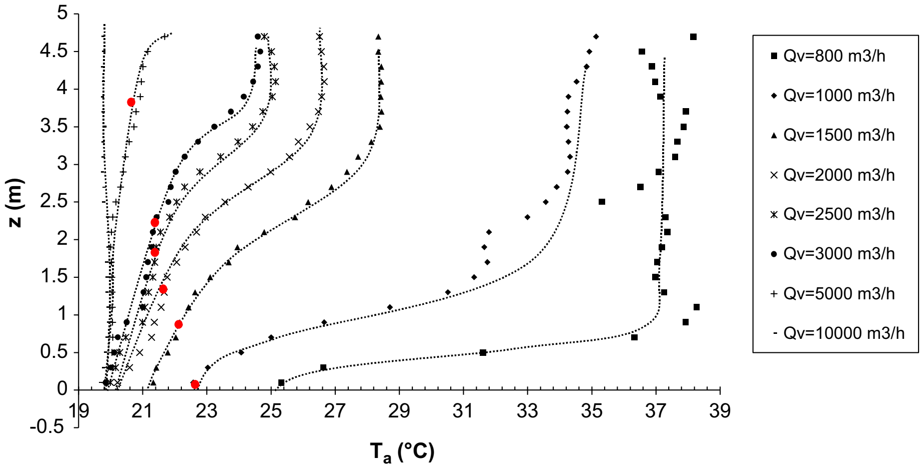


Fig. 10. Vertical temperature profiles outside the plume ($T_s = 200$ °C, $D_s = 1.54$ m). Interface height calculated from Skåret's proposed law [9].

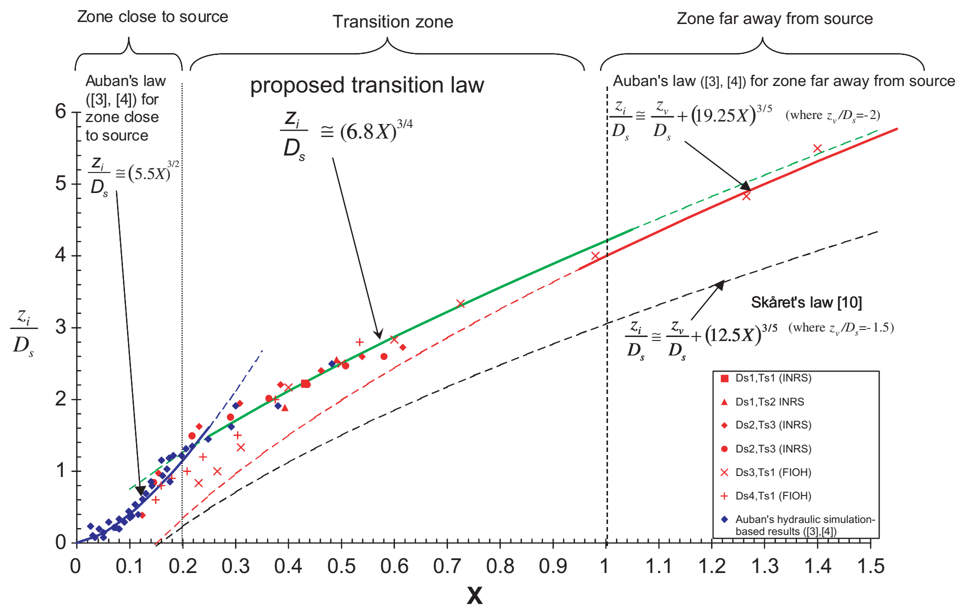


Fig. 11. Stratification height predictions.

formula [9] for each flow rate. In this calculation, we adopt a virtual origin located at $z_v = -2.2\,\text{m} \cong -1.5D_s$ in accordance with our experiments and Skistad's predictions [18], which advocate a height between 1 and 2 diameters below the source. Thus, even though Skåret's law [9] appears pessimistic in predicting the stratification height, we can consider that plume and ventilation flow rate equality characterises better the mixing layer lower zone between recirculated and cool zones.

## 8. Conclusion

Using the combined results obtained under different ventilation conditions and extending Auban's work [3,4], we have formulated laws enabling the stratification position to be approached. These laws depend on ventilation flow rate, source convective power and diameter. In keeping with Auban [3,4], we divide stratification heights into several zones. We suggest a definition of a transition zone in extension of the zone close to the source defined by Auban [3,4]. In this transition zone, we propose a law permitting enhanced consideration of the gradual disappearance of plume dependence on source geometry. All the recorded experiments support Nielsen's proposal [16] that radiation effects do in fact affect stratification thickness and not its height. Finally, our experiments appear to show that Skåret's predictions [9], based on flow measurements in an infinite space, would tend to predict stratification heights lower than those really obtained. These observations, which are often used when sizing DV installations, therefore turn out to be reassuring. Summarizing our observations, Fig. 11 consolidates on the same graph the three successive development laws for $z$ with respect to variable $X$ in each zone.

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