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AN ISOTHERMAL AIR CURTAIN FOR ISOLATION OF SMOKING AREAS IN RESTAURANTS

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ABSTRACT

An isothermal air curtain for isolation of smoking areas in restaurants was designed, built and evaluated in a test facility using oil-smoke visualisation and tracer measurements. The test facility was a ventilation test room set up as a small restaurant, with tables, chairs, person simulators (cylindrical heat sources) and balanced mechanical ventilation. Fresh air was supplied in the non-smoking section of the room, exhaust air drawn from the smoking area, and the air curtain was attached to the ceiling between the two sections. The air curtain was a plenum chamber with adjustable slot width and mounting angle fed by a supply fan drawing air from the smoking section of the room. For reasonable room ventilation rates for a restaurant (11 l/s per person supply and exhaust air), the optimised air curtain yielded tracer concentrations in the non-smoking section as low as 5 – 10 % of the values measured at the same time in the smoking section. The limiting factor in the performance of the curtain was found to be the ability to properly supply enough air to the clean-air side of the curtain to prevent recirculation of polluted air from the smoking area into the non-smoking section. This study demonstrates that an isothermal air curtain solution to control contaminant spread need not necessarily require excessive ventilation rates and prohibitive operating costs.

KEYWORDS

Air Curtain, Tracer Testing, Airflow Visualisation

INTRODUCTION

The new amendments to the Norwegian Smoking Law of 1988 require that at least one-half of the tables in a restaurant must be designated as non-smoking and that non-smoking areas are to be kept smoke-free. Erection of physical barriers to achieve compliance with the law is, however, not required. Cigarette smoke in non-smoking areas is considered to be a ventilation problem that requires a ventilation solution.

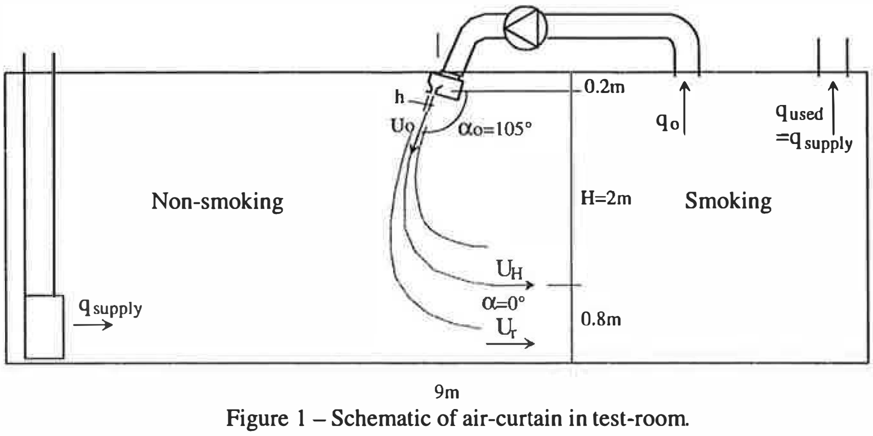

Figure 1 – Schematic of air-curtain in test-room.

One possible approach to keeping one area of a room smoke-free while people are smoking in another area of the same room is with an air curtain. Air curtains have been the subject of a number of research papers since the mid-1970's, primarily as a means of controlling heat loss from entrances to buildings during winter. Less common are applications where isothermal air curtains have been studied for use in contaminant control. Li and Peng (1994), for example, examined a push-pull air curtain in a scale-reduced model that was then implemented to control duck down pollution in a factory in China. As another example, Ho, et. al. (1994) used CFD to design an air curtain to control the spread of maleic anhydride in a polymer manufacturing facility.

This paper presents results of smoke and tracer testing of an isothermal air curtain for controlling the spread of cigarette smoke in restaurants. The study was carried out in the ventilation testing room of the Norwegian Building Research Institute.

DESIGN OF THE AIR CURTAIN

The test facility was a 9m x 6m x 3m ventilation test room set up as a small restaurant, with tables, chairs, person simulators (100 Watt cylindrical heat sources) and balanced mechanical ventilation. Fresh air was supplied in the non-smoking section of the room, exhaust air drawn from the smoking area, and the air curtain was bolted to the ceiling between the two sections (see Figure 1). The air curtain was a plenum chamber (see Figure 2) with adjustable channel width and mounting angle fed by a supply fan drawing air from the smoking section of the room.

The equations below were used for the design of the air curtain. A cross-section of the room is shown in Figure 1, with arrows denoting initial locations for supply and extract air. The isothermal air curtain is supplied with air from the smoking section. The non-smoking section is supplied with as much fresh air as is extracted from the smoking section, yielding balanced mechanical ventilation in the room.

The necessary impulse in the air curtain is determined by the pressure difference between the smoking and non-smoking sections. The air velocity between the zones, U_r is chosen = 0.25 m/s. This velocity corresponds to a dynamic pressure = $0{,}6 \cdot U_r^2$ =0.04 Pa, which is the pressure difference between the zones.

Assuming the jet centreline has become horizontal approximately 0.8 m above the floor, H is approximately 70% of the height from the floor to the air curtain channel. An analysis of the energy-momentum balance in the jet gives (from Skåret, 1999):

$$y = M(\cos\alpha - \cos\alpha_0) / \Delta p = H \qquad (1)$$

Where M is the momentum flux per unit length of curtain, Δp is the pressure difference, and α, α_0 and H are as defined in Figure 1. Eqn. 1 yields:

$$M = H \cdot \Delta p / (\cos\alpha - \cos\alpha_0) = 2.0 \cdot 0.04 / (1 - (-0.26)) = \underline{0.063} \text{ N/m}$$

We can now use:

$$M = \rho b_0 U_0^2 \; i/\varepsilon \qquad (2)$$

Where U_0 is the start velocity in the curtain, b_0 is the start jet-width, i is the net momentum flux coefficient, taking into account momentum losses, ε is the contraction coefficient for a nozzle, and ρ is the density of air.

We can with good approximation set the channel width $h = b_0\, i/\varepsilon$ to determine the necessary start flowrate in the air curtain. If we choose h = 0.01 m as a starting value, then:

$$U_0^2 = M/(h*\rho) = 0.063 / (0.01*1.2) \qquad (2a)$$

$U_0 = \underline{2.29 \text{ m/s}}$

$q_0 = 2.29 \cdot 0.01 = 0.0229 \text{ m}^3\text{/s,m} = 23 \text{ l/s,m}$ (For 6 m channel = $\underline{138 \text{ l/s}}$)

($q_0 = 497 \text{ m}^3\text{/h}$)

The velocity in the jet centre 0.8 m above the floor, U_H, is found approximately from the general equation for a free jet from a channel where the jet length is set to approximately 3m and the vent constant ≅ 7.0:

$$U_H = U_0 \cdot \sqrt{K_2 h / x} = 2.29 \cdot \sqrt{7 \cdot 0.01/3} = \underline{0.35 \text{ m/s}}$$

The total air volume in the jet at U_H (after 3 m) = q_H

$$q_H / q_0 = \sqrt{2} \cdot U_0 / U_H = \sqrt{2} \cdot 2.29 / 0.35 = 9.25 \qquad \text{or } q_H = 9.25 \cdot 23 = 213 \text{ l/s,m}$$

The entrained airflow into the jet at 3 m = q_H-q_0 = 213 – 23 = 190 l/s,m
The entrained airflow from the non-smoking section = 190 / 2 = 95 l/s,m (For 6 m channel = 570 l/s)
To prevent recirculation from the curtain, The fresh air supply to the non-smoking section should be greater than or equal to the entrained airflow from the non-smoking zone:

$$Q_{supply} = 570 \text{ l/s} \quad (=2052 \text{ m}^3\text{/h})$$

This air volume passes under the air curtain with velocity U_r = 0.25 m/s. The height of the column passing under the curtain is then = 0.095 / 0.25 = 0.38 m, which corresponds reasonably with the available height under the jet.

A necessary condition is that the supply air does not short-circuit to the smoking section before the curtain entrains it.

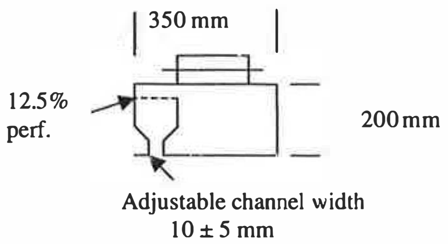

Figure 2 – Cross section of the air curtain

TESTING OF THE AIR CURTAIN

The air curtain was evaluated and optimised using smoke and tracer releases. Tracer concentrations were measured with a Bruel & Kjær Multi-gas Monitor Type 1302 and Multipoint Sampler and Doser Type 1303. Concentrations were measured at 5 locations in the test-room: At the exhaust vent in the smoking section, at a height of 1.5 m in the middle of the smoking section, at two locations at a height of 1.5 m in the non-smoking section, and in one of the supply vents in the non-smoking section. Tracer was released at three locations in the smoking section and dispersed with small fans to ensure well-mixed conditions.

Tests were done with air curtain slot widths of 10 mm, 5 mm and 3 mm, with varying mounting angles of the curtain with respect to the non-smoking zone (+15, 0 and –15), with varying supply and extract airflow rates and with several different non-smoking section supply air configurations.

RESULTS AND DISCUSSION

Smoke tests suggested that the curtain was effective at holding smoke out of the non-smoking section of the test room. However, the air curtain could not, in any of the tests, maintain a *completely* smoke-free environment in the non-smoking section. There was always at least a small but noticeable degree of transfer of smoke across the curtain. This was confirmed in the tracer tests. Figure 3 shows an example of a tracer test in the test room. The tracer release was started at approximately 17:00 and shut off at around 17:30. Concentrations rose quickly at the extract air and smoking section measurement locations, and levelled off at approximately

45 parts-per-million (ppm). The total tracer release rate from the three release points was 9 ml/s = .032 m^3/h with a supply air flow of 1500 m^3/h. Tracer concentrations in the non-smoking section were dramatically lower during the release, demonstrating the air curtains' effectiveness at containing the contaminant. Measurable concentrations of tracer in the supply air were evidence that there was a small degree of short-circuiting between the exhausts and supply ducts, but not enough to account for the tracer concentrations in the non-smoking section of the room.

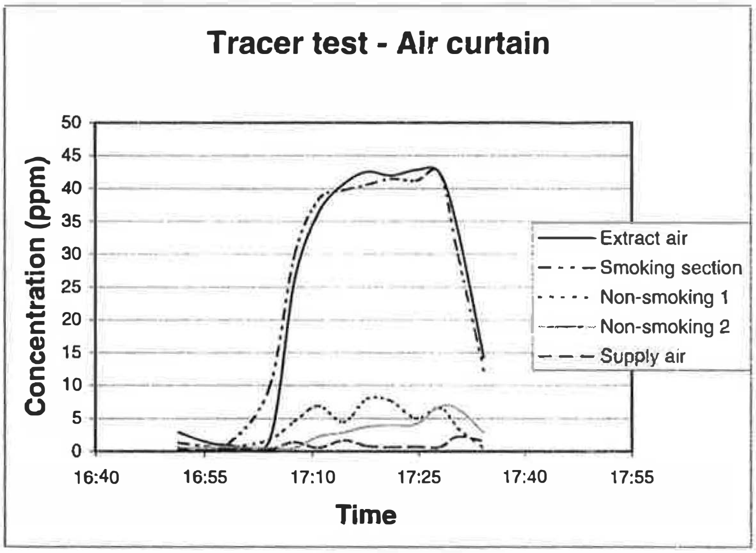

Figure 3 – Tracer test of air curtain.

A 5-mm slot width was clearly superior to both 10-mm and 3-mm slot widths in both smoke and tracer tests. The air curtain also performed optimally when directed at an angle toward the smoking section and with as much source air as possible (in this case the maximum output of the curtain supply fan was 600 m^3/h, or 100 m^3/h per meter of air curtain). It is interesting to note that the air curtain flowrate in this study was a small fraction of the flowrates in the air curtains discussed in Li and Peng (1994) and Ho and Goodfellow (1994). Li and Peng used a curtain with a 70-mm slot width with a velocity of 3.9 m/s, which corresponds to 983 m^3/h per meter of air curtain. Ho and Goodfellow do not give the curtain length or slot width in their paper, but the velocity was 10.2 m/s and the air curtain flowrate was 13,600 m^3/h. The more modest flowrate in the air curtain in this study implies better comfort for patrons and a more reasonable operating cost for the proprietor.

Equally good performance was achieved with a non-smoking section supply airflow of 2000 m^3/h down to about 1500 m^3/h (3/4 of the design value). A fresh-air supply of 1500 m^3/h (416 l/s) for a restaurant with a floor area of 54 m^2 yields a quite reasonable per-person fresh-air supply of 11 l/s (using the recommended design value of 1,4 m^2/person in the Norwegian Building Code).

A noticeable decline in performance occurred for a room supply rate below 1500 m^3/h. The air curtain also performed relatively poorly with displacement ventilation from floor-based supply air terminals, yielding tracer concentrations in the non-smoking section 30-60% of the well-mixed value in the smoking section. The bulk of the non-smoking section supply air short-circuited across the floor under the curtain and was therefore not available to provide the induced flow necessary to prevent eddies of polluted curtain air from recirculating into the non-smoking section. Considerably better performance (tracer concentrations in non-smoking section down to 5-10% of concentrations in smoking section) was achieved using ceiling-mounted low-impulse supply air terminals.

CONCLUSIONS

This study demonstrates the feasibility of using an air curtain to provide improved air quality to non-smokers in a space to be occupied by both smokers and non-smokers. Both smoke and tracer tests demonstrate that the air curtain is effective at containing pollutants in the smoking zone of a room partitioned with the air curtain. The results suggest, however, that a completely smoke free environment is not attainable in a section of a single room if smoking occurs in another part of the same room and they are partitioned with an isothermal air curtain. A small flux of contaminant across the partition appears to be unavoidable.

The air curtain performed equally well with a room-supply airflow down to 3/4 of the design value (11 l/s per person), provided that the supply air was well mixed in the non-smoking section before entrainment into the air curtain. In addition, the air curtain start flow (100 m^3/h per meter of air curtain) was substantially smaller than in previous related studies, demonstrating that an air curtain solution need not necessarily require excessive ventilation rates. This is important for a restaurant application both in terms of comfort for patrons and operating costs for the owner.

ACKNOWLEDGEMENTS

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