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Analysis of the influence of the return position in the vertical temperature gradient in displacement ventilation systems for large halls

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ABSTRACT

Displacement ventilation systems are widely used in spaces of small and medium heights (up to 7.5 m), taking advantage of their high efficiency in removing contaminants by means of the air stratification. This outcome usually hides major drawbacks compared to admixture systems, such as inadequate temperature gradient in the occupied zone and low cooling capacity. On the contrary, its use in large spaces with high ceilings displays the best features of the system, provided the return is placed near the ceiling. When, due to architectural reasons, this option is not feasible, alternatives for the return position are assessed using simulation tools that result in excessive time consumption during the design stage. In this article a simple Mundt's equation based iterative process is proposed to quickly evaluate the influence of the return height in the vertical temperature gradient and the additional cooling load due to overheated ceiling. It has been applied to the case of Madrid airport new terminal, and their results have been compared to a CFD simulation, with a reasonable degree of accuracy for an initial stage of a design process. The results show that the higher the return is placed, the lesser airflow rate is needed to match the additional cooling load due to radiation from the ceiling. The calculation process also shows that Mundt's radiant heat exchange coefficient is far from being constant, for it is affected by the height of the return point, and takes values much greater than the usually accepted.

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1. Introduction

Mixing-type diffusion systems have traditionally dominated air conditioning of large spaces [1]. The major cause for this prevalence is the capacity to offset high cooling loads while maintaining uniform hygrothermal conditions in the occupied area with relatively low air flow rates [2]. Its main disadvantage, however, is the low air quality obtained [3].

Displacement ventilation systems, whose origins are related to the high demanding ventilation needs in industrial uses [4], are the most efficient way to achieve good air quality due to its high performance when eliminating sources of pollution in the occupied area. By means of a high thermal stratification, a vertical gradient of concentration of contaminants is produced, which allows the system to easily remove pollutants with a return outlet near the ceiling [5].

Nevertheless, when a displacement ventilation system is used in rooms with great ceiling heights, overheating of the roof and stagnation of warm air masses near the ceiling occurs. This situation is worsened when, due to architectural decisions, air cannot be exhausted near the ceiling. In this case, if a direct discharge of stagnated air through skylights is forced, air currents due to infiltration through doors and openings are generated, and a mismatch of environmental conditions in the occupied zone occurs, which prevents the displacement diffusers to function properly.

If the return outlets are placed at low height, the main consequences are:

- Vertical temperature gradient in the occupied zone is greater than the acceptable [6].

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Nomenclature

Φ_s	Specific sensible cooling load (W/m^2)
T_s	Supply air temperature (°C)
T_r	Return air temperature (°C)
T_i	Indoor air temperature (°C)
Q_s	Specific supply air flow rate (m^3/h m^2)
$\alpha_{c,f}$	Convective heat exchange between air and floor (−)
$\alpha_{r,c}$	Radiant heat exchange between air and ceiling (−)
h_i	Surface heat transfer coefficient between floor and air (−)
H_R	Return point height (m)
H_c	Ceiling height (m)
TVG	Temperature vertical gradient (°C/m)
PPD	Predicted percentage of dissatisfied (%)
Θ	Dimensionless temperature

– The air is returned with lower temperature, which implies a reduction of the cooling capacity of the system.

This drawback can be solved by increasing the air flow rate, which leads to excessive discharge velocities and disturbing currents in the occupied zone. In contrast, when using lower supply air temperatures, in addition to the increase in energy consumption, the temperature of the occupied area exceeds the comfort conditions limits.

Optimum return position is a design parameter for which no references are found neither in design handbooks nor in scientific literature, which usually refer to lower ceiling heights [7] or assume that return is placed at ceiling level. Though other important items are also developed in this article, this circumstance alone would justify the following study.

In this work it is analyzed the influence of the return height of this element on the thermal parameters of the system, paying special attention to the vertical temperature gradient, as well as, due to its influence in the energy performance of the system, the airflow rate needed in each case to match the cooling loads [8,9]. To carry out the research, a simplified iterative calculation process has been used, and the results compared to the obtained with a CFD simulation. This method has been applied to a representative new building such as the Barajas airport new terminal, by Estudio Lamela and Richard Rogers Partnership [10].

2. Material and methods

The satellite building of the new Barajas airport terminal is a rectangular building several hundred meters long with a constant cross section of 37 m width [11]. The ground floor level is occupied by technical systems. The roof has a characteristic wave like shape in section, and is placed at an average height of 18 m, ranging from 15 to 23 m (Fig. 1).

Air conditioning of lounge areas is provided by the displacement ventilation system that is analyzed throughout this work, supplemented with jet nozzles diffusers all along the East and West glass facades. This solution allows to offset external heating and cooling loads, as well as to eliminate cold drafts down the facade and the risk of condensation in glazed surfaces and thermal bridges. It also creates an effective climate separation area that makes internal zone independent from the perimeter areas.

As architectural decisions prevented return air ducts to be visible along the ceiling, and in order to avoid the aforementioned disadvantages of so high a ceiling, mainly radiant asymmetry and warm air stagnation near the ceiling, an "ad-hoc" solution of a vertical totem was proposed, as it is shown in Figs. 1 and 2.

This element enabled to place the return outlets at its upper point keeping the ducts from being visible at all, and to cool the return air at this point by means of a set of five air nozzles placed in the upper part of the element (Fig. 3). With this solution, warm air stagnation near the ceiling and roof overheating was conveniently avoided. Due to geometry problems, a return point height of 13 m was finally adopted.

2.1. Usual design criteria for displacement ventilation systems

When the emission of pollutants is uniformly distributed, as in rooms with high occupancy, the system design is based on the control of vertical temperature gradient, in order to maintain the comfort design parameters in the occupied area [12], namely air temperature at 1.80 m height [13], maximum air velocity [14], radiant asymmetry with the walls [15] and temperature difference between head and feet [16], within specified limits.

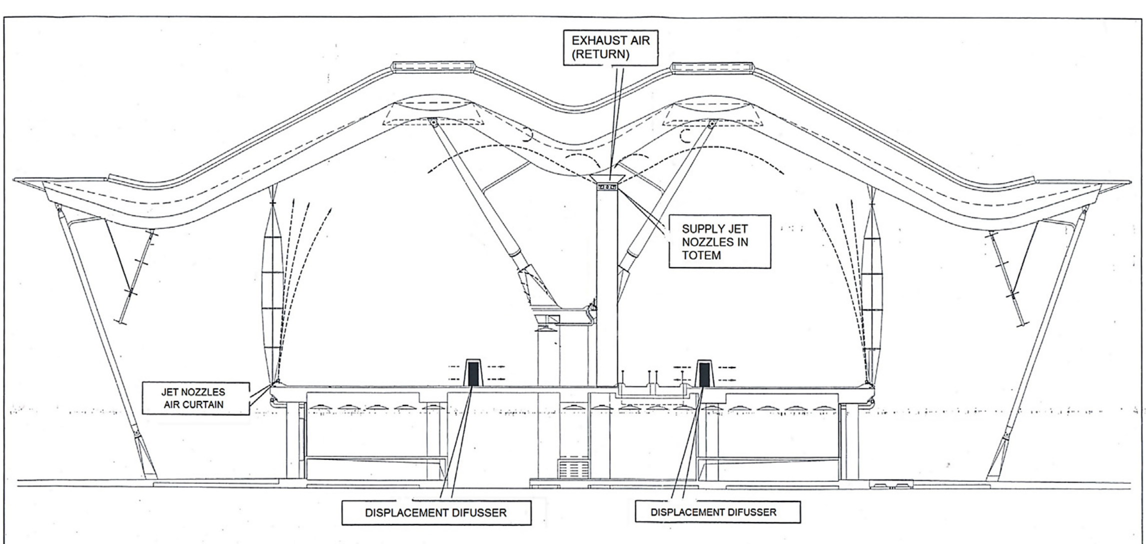

Fig. 1. Cross section showing air diffusion systems.

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