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An Experimental Analysis and Modeling of Thermal Environment Control of Air Distribution Systems for Chilled Food Manufacturing Units

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Abstract:
Chilled food manufacturing units in most of the situations have high ceilings to accommodate various levels of height equipment and manufacturing lines. The units are normally cooled by fan coil units located at ceiling level in a similar way to cold rooms, resulting in high velocities, uncomfortable environments for the workers and high energy consumption. To address these problems, this research investigates the influence of various air distribution arrangements on air velocities and temperatures in a laboratory scale test facility and by means of a CFD model. The intention was to achieve low velocities and uniform temperatures at low level to get temperature stratification between floor and ceiling levels to minimize energy consumption. Experimental and CFD modeling results proved that supplying air at mid level in the space through fabric ducts 'socks' could provide temperature stratification of the order of 70C between floor and ceiling level and energy savings in the region of 9% compared to ceiling mounted fabric ducts and 23% over non-ducted cooling coils mounted at ceiling level.

Keywords: CFD, Chilled Food Industry India, Fabric Ducts, Energy Consumption.

1. INTRODUCTION:

Current food processing takes place in large spaces with high ceilings. In these spaces cooling is normally provided by ceiling mounted fan coil units drawing air from the space and discharging it back at high velocity directly through duct mounted diffusers.

These systems employ the mixing cooling principle by which air is mixed in the entire room volume. This results in fairly uniform environments in terms of temperature and contaminant concentration but leads to energy wastage as all the air in the space volume is cooled to low temperature even though only the air at a low level, just above the food processing lines needs to be maintained at a low temperature for food safety and shelf life. The air distribution patterns in large spaces can be obtained from experimental tests including flow visualisation studies and from modelling approaches. Studies to date have focused on air distribution in large spaces in commercial buildings for ventilation and air conditioning applications to provide thermal comfort for the occupants and reduce energy consumption, and in cold rooms where the priorities are to maximise the holding volume and provide uniform temperatures in the space. Very little work has been reported in the literature on air distribution in chilled food factories where the objective is to maintain the temperature at low levels for food safety and quality but also reduce thermal discomfort for the occupants in the space. Regarding experimental studies dealing with air distributions systems, Rees and Haves [1] studied the air flow mixing and overall temperature gradient in a room with displacement ventilation and chilled ceiling for office environments.

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The authors found that significant air mixing reduces temperature gradients in the upper part of the room. Cheng et al. [2] analysed the effect of different locations for the supply and return grilles on thermal comfort and energy savings. The authors showed that temperature stratification in the space can provide both energy savings and thermal comfort for the occupants. Lin and Tsai [3] studied the effect of supply diffuser position and supply air flow rate on the thermal environment of an indoor space. The authors reported that for a given diffuser, the temperature gradient in the space reduces as the supply air flow increases due to greater mixing between the room and supply air. Menwhile, Jurelionis et al. [4] investigated the impact of the air supply method on the ventilation efficiency in a test chamber. In this investigation, the aerosol particle dispersion with different air distribution methods was analysed. Results showed that the one-way mixing ventilation ceiling diffuser with low flow rate was more efficient in terms of ventilation in comparison with the four-way mixing and high air exchange rates.

It was also concluded that the displacement air distribution method was less efficient than the mixing ventilation in terms of air removal. Rhee et al. [5] evaluated the performance of an active chilled beam system in terms of uniformity for an indoor thermal environment in a fullscale test bed. The authors reported acceptable thermal uniformity with the active chilled beam system even at low air flow rates. Airflow modelling techniques have been developed over the last 30 years to provide a better understanding of air flow patterns and temperature distribution in large spaces including cold rooms. Smale et al. [6] reviewed CFD modelling applications for the prediction of airflow in refrigerated food storage applications. It was reported that the k-e turbulence model was not accurate enough to be used in many refrigerated food storage applications and the RSM (Reynolds Stress Model) provided higher degrees of accuracy.

Ambaw et al. [7] reviewed the application of CFD for the modelling of post-harvest refrigeration processes. The finite volume method with the upwind differencing scheme was identified as the most common solution method. In addition, it was reported that the Reynolds Stress Model (RSM) provides more accurate predictions compared to the conventional k-e model but the k-e model is more commonly used due to its lower computational requirements. Laguerre et al. [8], in order to avoid the computational time of a CFD model, created a simplified model using the knowledge obtained from experimental measurements. The model was separated into zones and heat balance equations for each zone were developed. The simplified model was found to predict the product cooling rate and the final product temperature at different positions in the cold room quite well. The air flow in the space was solved using the Reynolds averaged Navier Stroke equations (RANS). The standard k-e, RNG k-e and standard k-x two equation turbulence models were considered and the SST k-x was found to produce the most accurate predictions of air pressure drop and produce temperature when compared to experimental data.

2. PROCEDURE:

The initial stage of this research was focused on understanding the air flow and temperature variation in existing chilled food facilities using measurements and CFD modelling. The research reported in this paper deals with the experimental investigation and CFD modelling of different air distribution arrangements to achieve temperature stratification in the space and reduce energy consumption. The experimental test rig was established using an environmental chamber constructed with insulated cold room panels. The chamber dimensions are 2.9 m (H) 6.6 m (L) 3.5 m (W). Cooling in the chamber was provided by an evaporator coil served by an R404a condensing unit situated outside the test rig in the ambient air. A schematic diagram of the layout of the test rig is shown in Fig. 1. For the initial experiments, two air distribution methods were tested.

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The first configuration is used in a large number of chilled food manufacturing facilities. In the case of the air distribution via fabric duct, it appears as an attractive option due to its practical design, reduced acquisition and maintenance cost and homogeneous air flow if compared to metal-based air distribution systems. Air temperature measurements in the chamber, using T-type thermocouples, were taken at 4 sections along the length of the chamber and 4 sections along the width of the chamber (Right-wall, Right-centre, Left-centre and Left-wall) and at three heights, knee level, head level and ceiling level. In total, 48 temperature sensors were installed. The thermal load from occupants (OC) was simulated by 4 rectangular boxes of 1.6 m2 surface area each wrapped with trace heater elements, 150 W each.

The measured temperature at the top of the occupants was on average of 14 C. A variable speed controller was also used to control the supply air. The logging interval of the data was set to 10 s. The time for each test was 17 h. Table 1 presents the measurement uncertainties of the used sensors. The air temperature in the test chamber was controlled using a temperature controller with the thermostat located on the evaporator air suction side and set to 9.7 C. 2.2. CFD model details The dimensions of the scaled model volume are those of the experimental test room. The HVAC system consisted of a single evaporator coil circulating the air. As in the case of many existing processing facilities, the evaporator is operated with 100% recirculated air. The evaporator is controlled by a thermostat with 9.7 C air-of set point temperature.

Mesh generation:

The computational domain was discretized with an automatic mesh method, with mainly tetrahedral cells (with hexahedral cells in the boundary layer). The mesh density was gradually refined near the building wall, the fabric duct and other surfaces in the space. The final mesh size consisted of 9.4 million elements for the case of the plain evaporator and 9.6 million elements for the case of fabric duct.

The element dimensions for both cases varied between 0.02 AND 0.06 m (0.02 for lighting, occupants and sock. 0.04 for evaporator outlet. 0.06 for productions evaporator body and walls). The finer mesh sizes were located near the wall surfaces, where 4 inflation layers were also employed to capture the effects of the boundary layer. The final model mesh was generated following a mesh independency study. The simulation time for each steady-state case was 8 h, with an average of 3000 iterations, on a 2.5 GHz, 64 GB RAM, Intel Xeon Processor (2 processors) with 48 parallel threads.

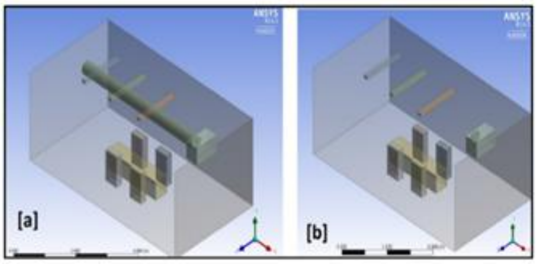

Fig.1: 3-D models (a) with Fabric duct and (b) Plain evaporator

The convergence criteria for the independency study were set to reach at least a 10–5 residual error for continuity and an average temperature tolerance of ±0.5 C. The 3 values of interest were the average temperatures at knee, head and ceiling level height. The initial mesh size was at 4.6 million cells and the solution convergence criteria were met at 3000 iterations. In addition, comparing with experimental values the mesh with 9.6 million cells size provides a good prediction.

3. RESULTS AND DISCUSSION:

This section discusses the results of the experimental measurements and CFD modelling of the thermal environment arising from the air distribution system via plain evaporator coil and fabric duct. Then the analysis of an air distribution system is presented that is located at a medium level as an alternative configuration. Finally, the energy consumptions of the refrigeration system with the different air distribution configurations are compared.

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CFD modeling:

Fig. 6a shows the air temperature distribution in the space with a supply air temperature from the evaporator at 7 C. The temperature in the bulk of the space varied between of 7.0 C and 8.0 C considering the same measurement points of the experimental test. In addition, it can be observed that higher temperatures were found close to the occupants due to the heat gains from those. This agreed with the data collected from the measurements which also showed the highest temperatures at a low level, mainly around the occupants. Modelled air flow velocities in the space were found to be significantly high ranging from 0.02 to 3.0 ms. As also noted experimentally, it is observed that the highest air flows were found at ceiling level due to the direct air discharge from coil employing a small air flow area.

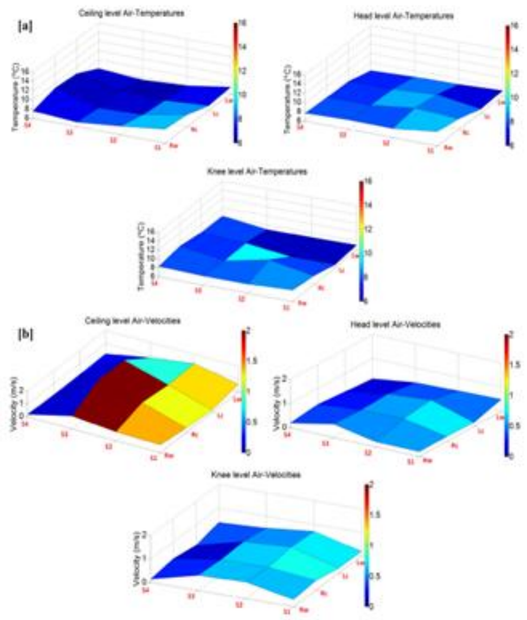

Fig.2: Measurements at different heights; Knee Level, Head Level and Ceiling Level. [a] Temperature profiles and [b] Velocity profiles

It can also be observed that the air flow patterns over the space are not homogeneous and that air velocities are also relatively high close to the front wall. The air flows along the ceiling to the front wall, and then it flows down next to the wall until it reaches the floor. Then, recirculation takes place in an area between floor level and ceiling level. Based on the CFD modelling results, it can be highlighted that this type of air distribution method tends to cool-down uniformly the whole volume of the space at very high and non-homogeneous air flow velocities leading to an excessive discomfort and non-energy efficient system.

- In general, the model shows a good level of prediction for the air temperature and velocity trend and distribution achieved in the space. From the results, the average absolute error across all test points in the space was found to be 0.73 C and 0.6 ms.

4. CONCLUSIONS:

This paper details result of experimental investigations and CFD modelling aimed at improving the efficiency of air distribution and temperature control systems in chilled food manufacturing facilities. The investigations were carried out in a test chamber which was set up to simulate conditions in chilled food manufacturing facilities. These facilities normally have high ceilings and are served by non-ducted evaporator coils or diffusers located at ceiling level providing temperature control in the space through the mixing principle. These distribution systems invariably result in high velocities which lead to uncomfortable conditions for operators and energy wastage.

A primary objective of the project was to demonstrate the feasibility of flexible systems that can be easily retrofitted onto existing air distribution systems and provide both energy savings and better thermal control conditions in the space through low air velocity supply and thermal stratification. Three alternative systems were investigated experimentally and by means of CFD models: a) air distribution through a round fabric duct at high level; ii) air distribution through a round fabric duct at medium level, and iii) air distribution through a D-shape fabric duct at medium level. The following conclusions can be drawn from the experimental and CFD modelling results:

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Experimental and CFD model results agreed that air distribution through fabric ducts result in lower air velocities and better thermal environments in chilled food manufacturing facilities compared to ceiling mounted non-ducted systems. Due to the low air discharge, velocities from the duct, even when mounted at ceiling level fabric ducts, develop a temperature stratification in the space.

When the air entering the cooling coil is drawn from a lower level in the space, the system can lead to energy demand reduction and savings of the order of 15%, as demonstrated by the test results. Energy savings can increase further if the air is drawn from medium level, cooled in the coil and supplied at medium level just to cool the area in which food processing takes place. The results from medium level supply showed energy savings of the order of 23% over a non-ducted coil at ceiling level and 9% over a fabric duct distribution system mounted at ceiling level. Fabric duct air distribution systems are very flexible and easily adaptable for the cooling of large high ceiling places.

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