



AALBORG UNIVERSITY
DENMARK

Aalborg Universitet

CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 5

Heiselberg, Per Kvols

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 5*. Department of Civil Engineering, Aalborg University.

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Priority School Building Programme: An Investigation into Predicted Occupant Comfort During the Heating Season in Naturally Ventilated Classrooms

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Abstract

Natural ventilation solutions can provide sufficient outside air to maintain adequate indoor air quality (IAQ), which can improve occupants' performance in classrooms and provide reductions in energy consumption for space conditioning. In this study, the effect of cool outside air and the vent opening configurations on IAQ and occupant thermal comfort in naturally ventilated classrooms during the heating season was examined. Dynamic and steady state computer simulations were performed to investigate the internal conditions of a naturally ventilated classroom, designed to meet the requirements of the Priority Schools Building Programme (PSBP) Output Specification. The modelled designs considered natural cross ventilation airflow through high-level top hung-out or bottom hung-in openings, and a stack (atrium). Dynamic thermal modelling results indicate that adequate IAQ and occupant thermal comfort could be achieved using natural ventilation. However, the CFD simulation results predicted occupant discomfort due to draughts in the regions close to the openings. Bottom hung-in vents reduced draught impact and the study also suggests moving occupants away from the draught zones to minimise the effect of discomfort draughts on occupant comfort. The air velocity and airflow patterns in the classrooms were influenced by the shape, size, location of internal openings, and the flowrate through the openings. This could be controlled by introduction of new openings with lower airflow rates through each opening.

Keywords – thermal comfort; CFD; dynamic thermal modelling; natural ventilation; draughts; classroom design; cross ventilation.

1. Introduction

Natural ventilation is an effective design solution for ventilating classrooms in temperate climates as it can deliver thermal comfort, acceptable indoor air quality (IAQ) [1], and offer lower energy consumption for space conditioning compared to mechanical ventilation [2]. However,

when designing for natural ventilation its suitability during the winter should be considered [3].

Low ventilation rates in classrooms have been shown to present a significant influence on students' performance with regard to attention, vigilance, memory and concentration [4]. Pupil learning can be affected by increased temperatures, humidity levels, poor air movement [5,6] and by indoor pollutants [7], all resultant of sub optimal ventilation.

Previous research on existing UK classrooms conclude that although thermal comfort in the heating season was considered acceptable, IAQ was sub-optimal due to poor implementation of building operation, resulting in low ventilation rates and consequently high CO₂ concentration levels [8,9]. Where openable windows are the only means of naturally ventilating a classroom, intermittent draughts in zones adjacent to open windows can result in occupant discomfort [10,11]. The Education Funding Agency in England has sought to address these ventilation design concerns through the Priority Schools Building Programme Facilities Output Specification (PSBP-FOS) as well as reviewing and revising Building Bulletin 101 [12] which is slated for publication in 2016 [13].

The PSBP documents are intended to outline good practice design and provide recommendation on the appropriate use of natural ventilation in order to ensure comfortable environments for occupants [14]. However, there is limited information available on suitable external design conditions that can achieve adequate IAQ without causing discomfort draughts using natural ventilation in typical classrooms during the heating season. The aim of the research reported here is to identify the external conditions in winter and the opening configurations during which occupant thermal comfort and acceptable IAQ can be achieved in naturally ventilated classrooms.

2. Methodology

In order to establish the suitability for natural ventilation of classrooms during the heating season, the ventilation performance of different scenarios in a typical UK classroom was explored. These included cross ventilation of a classroom using two opening configurations during a range of climatic conditions.

The building under investigation considered the 'finger block' school baseline design provided by PSBP [14]. A standard classroom layout was selected, with room height of 3.3m and depth of 7.8m [14], and floor area of 55m² [15]. For modelling purposes, the classroom (Fig. 1) was considered to be occupied by 29 students and two teachers (42.4W each) evenly distributed across the floor area, allowing a circulation area on the perimeter. The classroom included heat gains from electronic equipment, i.e. a PC (97W) and an interactive whiteboard (100W), and ceiling lights (640W) [16].

Single-sided ventilation was achieved by two operable windows of 1.1m by 0.675m located at a high level on the same external wall. An opening

(0.29m^2) located on the opposing wall, connected the classroom to a ventilation stack with the same width as the classroom and height exceeding the total height of the building (12.9m) and with a louvered opening at the top (0.12m^2). Two types of external operable openings have been considered: bottom hung-in [BHI] and top hung-out [THO].

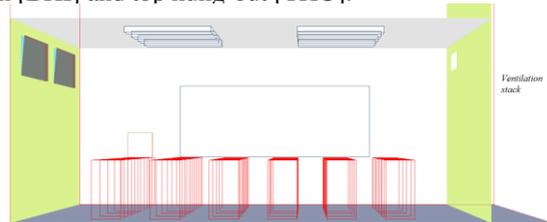


Fig. 1 3D view of the classroom studied (not to scale) showing the two bottom hung-in openings (left) and the ventilation stack (right)

3. Performance evaluation modelling techniques

To assess the performance of the ventilation strategies, acceptable environmental conditions for indoor air temperature, air velocity and CO_2 concentrations in the occupied spaces were considered:

The recommended average occupied level of CO_2 concentration for naturally ventilated classrooms is 1,500ppm and the maximum should not exceed the 2,000ppm for more than 20 consecutive minutes per day [17]. If ventilation rates of 8l/s are achieved then CO_2 concentrations can be less than 1,000ppm [11,22]. Air temperature delivered to the occupied zone at 1.4m above the floor level should be more than 5K below the normal maintained air temperature of 21°C [17]. The temperature gradient should be no greater than 3K between the ankle and neck level [19]. Air velocity and the air speed gradient in the spaces will be evaluated to assess draughts to reduce the risk of discomfort [20]; the mean air speed in the occupied zone should be less than 0.3m/s [17].

In order to establish the suitability of external conditions for natural ventilation of classrooms, computer simulations were carried out using two modelling techniques. Dynamic thermal modelling (DTM) simulations were performed in order to investigate the potential of the ventilation strategies to deliver acceptable levels of CO_2 concentration in the classroom during the heating season. Because DTM assumes that the air in spaces is well mixed, detailed airflow distribution in spaces was evaluated using steady state simulations using Computational Fluid dynamics (CFD) to predict the incoming airflow velocity, and the fresh air and temperature distributions.

DTM simulations were performed for the climatic conditions of a Test Reference Year for the location of Birmingham, UK using the software IES (version 2014.2.1.0). Two simulations were performed for the winter season in order to evaluate the ventilation performance of both single sided

ventilation and cross flow ventilation. The DTM simulations provided spaced-averaged values of ventilation rates and internal CO₂ levels on an hourly basis. Steady state simulations were performed with the general-purpose CFD code PHOENICS [21], using the finite-volume method and a structured grid. This well-established code has been selected due to its ease of use and its accuracy [22, 23].

Each type of opening ([THO], [BHI]) was evaluated for cross ventilation and four scenarios: buoyancy; zero angle; 45°; and 90° wind directions. For the wind driven ventilation, the average wind speed of the site under investigation was 3.6m/s. The performance of natural ventilation was explored for 15°C ambient temperature, this was selected as according to published work ambient temperatures of 13-14°C have been shown to provide occupants' comfort [24].

Further, for the study of the wind-driven ventilation, the domain decoupling approach was used to perform internal-external airflow simulations. This allowed the prediction of the flow around the building and the pressure values at the location of the openings, which were subsequently used as boundary conditions at openings for the study of the internal flow. This approach reduces the computational time and power required to simultaneously model the internal and external environments [25]. The external flow simulations were performed according to published work [26], further details of boundary conditions can be found in [27] and in [28]. In order for the solution to reach convergence, the two BHI openings were simplified and modelled without the angled-in opening but as a slot.

For the CFD simulations, the energy equation was solved for temperature, buoyancy was modelled with the Boussinesq approximation and turbulence using the k-epsilon model [29]. The solution was considered converged when: the spot values of each solved variables remained unchanged at a point in the domain; the errors of each variable in the finite-volume equation were reduced to an acceptable magnitude; source balance of less than 1% for each heat source or sink was achieved [26,27]. Mesh sensitivity studies were performed for the models of the internal and the external flows. For each case, the mesh that provided acceptable accuracy in the least computational time was selected and used throughout the modelling process. The total ventilation flow rate required for the occupants was 256l/s, considering 8l/s per person [12]. Once the required ventilation rates were established, the openable area required to achieve the flowrates was calculated (Equations 2.9 to 2.16 in [18]).

4. Simulation results

The results from the DTM demonstrate that it is possible to deliver adequate air quality in the classroom year round, whilst maintaining comfortable internal temperatures using natural ventilation [28]. Average values of CO₂ concentration in the classroom during occupied hours for all

ventilation scenarios were predicted below the average recommended for comfort (1,500ppm, [17]), with highest values (1,450 on average) predicted for the [BHI-90°] and [THO-90°] scenarios. However, the DTM assumes that the air in the classroom is well mixed and therefore this model is not suitable to check other aspects of the comfort requirements as detailed in the PSBP-FOS [17].

The CFD compared airflows of the classroom with [THO] and [BHI] windows with buoyancy driven natural ventilation and wind driven, with three directions of wind considered: perpendicular to the façade (0°), parallel to the façade (90°) and 45° to the façade. Table 1 compares the average airflows predicted by the CFD model for all 6 perturbations. These results suggest that the buoyancy driven flow delivers adequate air quality being greater than 8l/s/person, whilst the wind driven flows are, in general, slightly lower at around 7l/s/person. This suggests that the opening areas of the vents need to be larger in the wind driven models and optimal opening areas should be investigated in future work, nevertheless 7l/s/person is sufficient to maintain internal CO₂ concentration levels below the required 1500ppm. The predicted airflow rates of the tested ventilation strategies are very similar between [THO] and [BHI] with the exception of wind parallel to the façade where the airflow for [THO-90°] is about 60% of the [BHI-90°], possibly an effect due to the opening's design.

Table 1. Predicted indoor air conditions using CFD

Scenario	BHI Buoyancy	BHI 0°	BHI 90°	BHI 45°
Ventilation rates (l/s/p)	10.30	7.15	7.15	6.84
ΔT ankle-head (K)	0.23	0.52	0.62	0.52
Draught rating (%)	11.28	6.98	6.91	6.99
Av. velocity-ankle (m/s)	0.19	0.26	0.26	0.27
Av. velocity-seated	0.12	0.11	0.11	0.11
Av. velocity-standing	0.11	0.09	0.09	0.10
Scenario	THO Buoyancy	THO 0°	THO 90°	THO 45°
Ventilation rates (l/s/p)	9.59	6.82	4.71	7.18
ΔT ankle-head (K)	0.37	0.35	1.19	0.35
Draught rating (%)	10.14	7.46	1.72	3.14
Av. velocity-ankle (m/s)	0.20	0.18	0.18	0.14
Av. velocity-seated	0.11	0.11	0.07	0.07
Av. velocity-standing	0.09	0.08	0.04	0.06

Fig. 2 allows comparison of the airflow velocity draught plume for [BHI] and [THO] under thermal buoyancy, the figure shows measured velocities in a section of the classroom and the iso-velocity contour of 0.3m/s which is the draught limit in the heating season [17]. It is evident from these images that velocities in excess of 0.3m/s are confined within the draught

plume as well as at the exit vent into the stack. Air speeds within the [THO] draught plume are much greater than the [BHI], the latter, having traversed further along the ceiling, has reduced in velocity before dropping into the centre of the room. The draught plume from the [THO] also contains much cooler air and therefore, it is likely that the [THO] draught will cause more discomfort than the [BHI]. The CFD models predict that there is a low level (<0.1m AFL) draught in both ventilation configurations, but because this is so low it is unlikely to be perceived by the occupants.

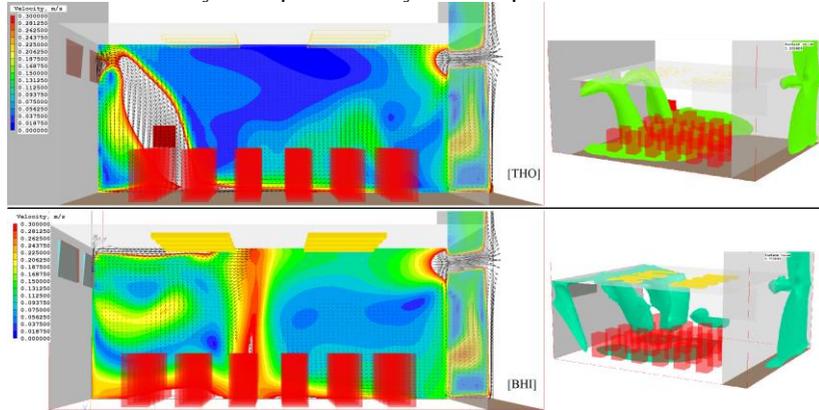


Fig. 2 Vertical sections (left) at the inlet/outlet and iso-velocity contours (for 0.3m/s) for the [THO] (up) and [BHI] buoyancy driven strategies

Table 1 shows the temperature difference between ankle and neck level and all variations of the model are well within the 3K temperature gradient required by the PSBP-FOS [16,18]. Fig. 3 compares the temperature distribution of a section through the classroom with [THO] and [BHI] windows when the driving force for natural ventilation is buoyancy. It is evident in both cases that the cooler outside air becomes sufficiently mixed with warmer internal air that it meets the requirement of being at least 16°C when it meets the occupied zone [17].

The flow of the cooler outside air differs greatly between the [THO] and the [BHI] opening configuration (Fig. 3). The BHI deflects the cool air towards the ceiling of the classroom where it flows across the surface of the ceiling by the Coanda effect, becoming tempered before eventually dropping towards the middle of the occupied zone. The temperature of the air in the occupied zone is fairly homogenous because the outside air has been tempered during its flow. In comparison, the [THO] orientation the cool external air flows in a downward direction delivering a region of cooler air (although above 16°C) to the occupied zone closest to the opening vents.

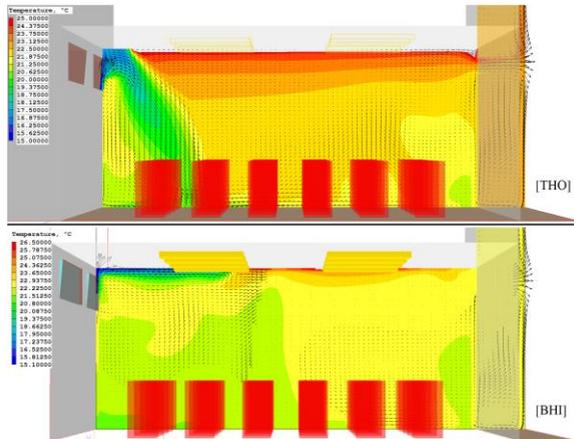


Fig. 3 Vertical sections showing temperature contours for the [BHI] and [THO] buoyancy

The CFD was further used to investigate the effect of wind driven ventilation on occupant comfort, in all scenarios the outside air became sufficiently tempered to enter the occupied zone at temperatures in excess of 16°C [28]. Fig. 4 shows the 0.3m/s iso-velocity contours for all wind driven variations and it is evident that the wind direction has a big effect on the formation of the draught plume and how it affects the occupied zone.

When the wind direction is perpendicular to the façade (0°) the draught plume leaves the ceiling earlier in the [BHI-0°] in comparison to the buoyancy driven ventilation, the velocity within the plume is also higher than with the buoyancy driven. The plume enters the occupied zone and presents velocities in excess of 0.3m/s to a wider area than the buoyancy driven, with the occupants closest to the vent the least affected by discomfort draughts (Fig. 4). For the [THO-0°], the draught plume drops closer to the vents such that it is occupants closest to the vents that are the most affected by velocities in excess of 0.3m/s. Unlike the [THO] for buoyancy, the [THO-0°] shows some Coanda effect with the air moving a short distance along the ceiling before falling to the occupied zone. This longer flow path has the result that the air velocity for [THO-0°] is slightly less than [THO] for buoyancy within the draught plume as it enters the occupied zone.

When the wind direction is parallel to the façade, there is little change in the draught plume for [BHI-90°] in comparison to [BHI-0°], and again the occupants closest to the vent are the least affected by draughts. However, in the case of [THO-90°] the draught plume drops immediately on entry to the classroom, suggesting that the greater buoyancy of the cooler outside air being the major driving force on the airflow (Fig. 4). The draught plume has velocities in excess of 0.5m/s adjacent to the façade but these velocities have reduced to <0.3m/s when it enters the occupied zone. The airflow through

the two vents in [THO-45°] converge together in the centre of the room creating a downward swirl that creates a plume of velocities in excess of 0.3m/s that is directed to a discrete location within the centre of the occupied zone closest to the vents. Again, the wind direction for [BHI-45°] has little effect on the shape and distribution of the draught plume.

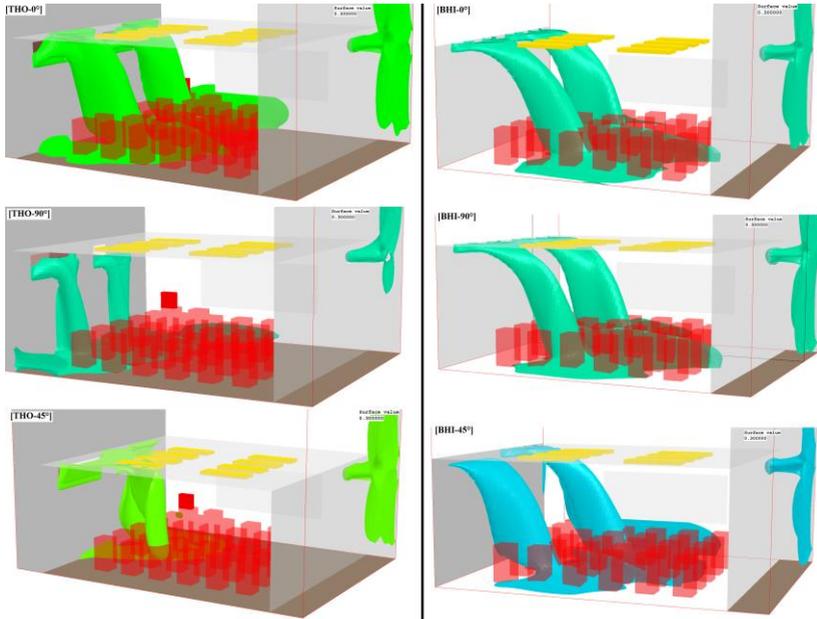


Fig. 4 Iso-velocity contours for all wind driven scenarios

The mean velocities at neck and ankle level (Table 1.) are all below 0.3m/s and the draught rating formula of ISO7730 has been used to ascertain the mean people dissatisfied [19]. The results from the draught rating formula suggest that the majority of the occupants will be satisfied, but the draught plumes suggest that there may well be areas of occupant discomfort where the air velocity is greater than the mean velocity. This is likely to be more of an issue with the [THO] configuration, where the air temperature of the draught plume is lower. Future work could investigate what temperature and velocity within a draught plume cause occupant discomfort, so as to better ascertain the predicted level of occupant dissatisfaction. Also, further work is required to determine the effect of lower ambient temperatures on the draught plumes and also whether different vent orientations/positions could reduce the effect of the draught plumes. Such investigations will be invaluable to design teams to optimise vents in order to provide the best natural ventilation experience.

5. Conclusions

The work in this paper acknowledges the limitations in DTM in establishing occupant comfort with respect to the nuisance draught criteria expressed in BB101 [12]. This paper reported the results of a numerical study focused on the external conditions and opening types during which thermal comfort and IAQ can be achieved in naturally ventilated classrooms. It was predicted that:

- All the natural ventilation scenarios evaluated achieved the comfort evaluation criteria with regards to internal air temperature and indoor air quality.
- In some cases, areas of high indoor air velocity could result in occupants' discomfort, although these areas were restricted to draught plumes, the temperature of which will also have an impact.
- The internal flow distribution varied significantly with regard to the opening configuration and wind direction scenario.
- The classroom zone close to the openings was affected by the most temperature variations and highest air speeds for [THO] whilst an area closer to the centre of the class was affected in the [BHI] scenario. Discomfort could be reduced by creating unoccupied zones in areas most affected by draught plumes.

This work will continue with further investigation of opening types and locations that could provide comfortable conditions for classroom occupants.

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