Perception of Thermal Comfort for Naturally Ventilated High School Classrooms in San Rafael, CA

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ABSTRACT: The primary intention of the case study is to analyze and define which environmental and architectural parameters affect thermal comfort of naturally ventilated high school classrooms for San Rafael, California. By using qualitative and quantitative analysis, the case study results suggest that the path of air flow should relate to the occupant within the space in order to remove internal heat gains and encourage the perception of thermal comfort. In addition to air flow, impact of solar gains are also significantly influential. If direct solar radiation is not controlled, the consequence of higher solar gains may challenge the potential of natural ventilation to achieve thermal comfort as a passive cooling strategy.

KEYWORDS: thermal comfort, natural ventilation, high school classrooms

INTRODUCTION

Comfort is defined as “a subjective response or state of mind, where a person expresses satisfaction with the thermal environment” [8]. However, comfort is not only a state of mind but can also be defined as a physiological response of a body’s balance of heat within a thermal environment [5]. For a naturally ventilated space which relies on operable apertures to provide fresh air and thermal comfort, indoor dry bulb and surface temperatures reflect external dry bulb temperatures [7]. Therefore, a climate’s external conditions contribute to the thermal comfort of occupants and may limit the potential of natural ventilation as a passive cooling strategy.

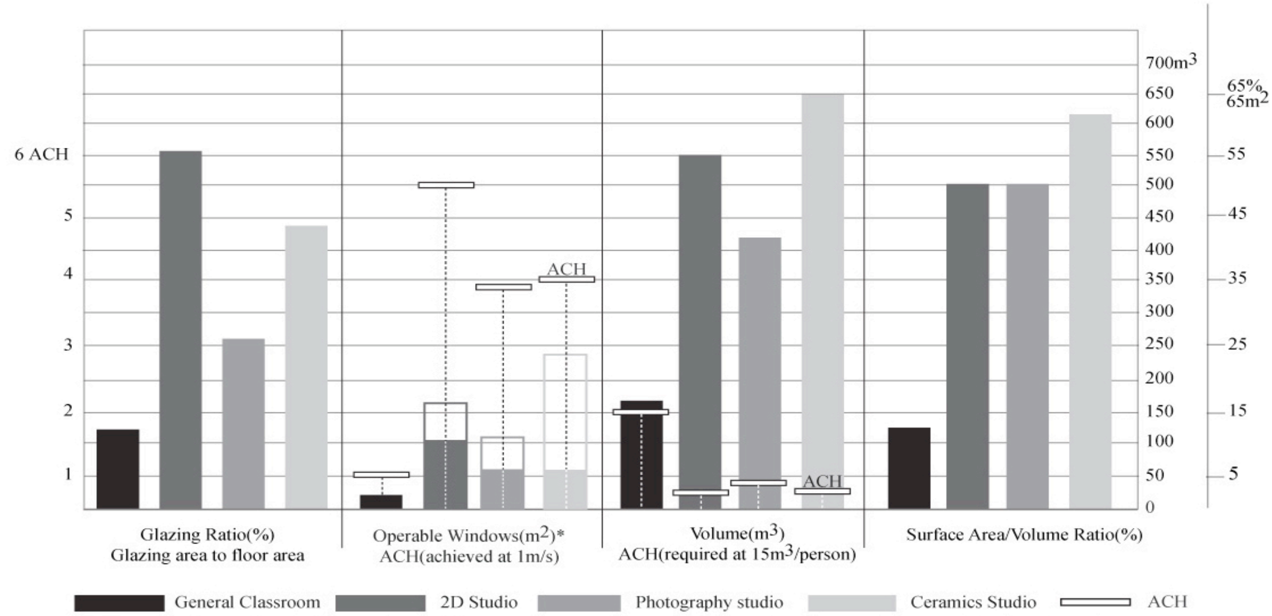
Brager and de Dear (1998) posit that occupants in naturally ventilated spaces accept higher indoor temperatures since they are allowed control over the thermal conditions of a space [4]. However, determining how operable apertures provide comfort to occupants of a space is complex, especially for highly occupied spaces such as high school classrooms. The thermal consequence of opening a window does not instantaneously provide thermal comfort to occupants. The ability of natural ventilation to achieve thermal comfort as a passive cooling strategy is influenced by multiple environmental and architectural factors such as: internal and solar gains, external temperatures, wind pressure, and inlet and outlet aperture properties (e.g. size and location).

Due to San Francisco Bay Area’s Mediterranean climate, the feasibility of natural ventilation as a passive cooling strategy for providing thermal comfort is high. Across the Bay Area, high school classrooms either use natural ventilation during the mid season only or do not rely on mechanical cooling strategies at all to provide thermal comfort to students. Although the Bay Area is characterized as a mild climate, terrain and influences of a marine layer (fog) create pockets of microclimates that occur seasonally and diurnally [6].

As the marine layer naturally cools portions of the Bay Area Coast, inland climates such as San Rafael are unaffected by this natural cooling phenomena. They are exposed to high levels of direct solar radiation, lower wind speeds, and higher external temperatures. If not controlled, these three environmental characteristics coupled with high occupant gains may impact the potential for natural ventilation to achieve thermal comfort in high school classrooms. Therefore, the case study specifically analyzes four naturally ventilated high school classrooms located on one school campus in San Rafael. The case study’s main intention aims to highlight which environmental and architectural parameters influence natural ventilation’s potential as a passive cooling strategy for achieving occupant thermal comfort.

DESCRIPTION

Located twenty miles North of San Francisco and ten miles inland, San Rafael’s maximum external dry bulb temperatures for the months of June to August are on average 7K higher than neighbouring San Francisco. As the climate is not affected by the natural cooling of the marine layer, sky conditions for the months of May



*note: area of operable windows varies. solid portions represent area values confirmed through surveys (ACH are based on these values), while outlined boxes represent maximum available areas.

Figure 1.1: Characteristics of case study classrooms

through October are typically clear and mean daily direct solar radiation values are 210Wh/m^2. Coupled with high levels of direct solar radiation and average winds speeds of 2.7m/s, diurnal temperatures vary by 15K and mean maximum temperatures reach 27.5C during the months of June through October.

The case study evaluates three cross ventilated art studios (drawing/painting, ceramics, and photography) on the West side of campus and one single sided ventilated general classroom. Each art studio is one story and floor areas range from 90 to 110m^2. The studios are passively cooled via cross ventilation while mechanical heating is supplied during mid October to mid April (see Figure 1.1 for further details).

Approximately 30 meters to the South is a two story academic building which houses general classrooms and offices. Both spaces flank a central two meter wide corridor and are designed to be mechanically cooled and heated with a set comfort range of 18-24C. Except during the mid-season, these 54m^2 classrooms depend on single sided ventilation to achieve thermal comfort.

The students of the co-ed high school range from fifteen to eighteen years old and are not required to wear uniforms. An average class size is eighteen students and one teacher. The school year begins on the second to last week of August and ends for summer break after the first week of June. The school is occupied for 1170 hours during the academic year and class periods are 80 minutes long. Typical school hours are 08:00 to 15:00, with a lunch break between 12:00 and 13:00.

METHODOLOGY

The case study is analyzed using both qualitative (field surveys and interviews) and quantitative (field measurements and parametric analyses) methods. Two site visits, on June 4th and June 7th of 2008, consisted of taking spot measurements within the three art studios for internal dry bulb temperature. A two page occupant survey was given to the three art teachers in order to collect information regarding thermal and visual comfort. In addition, semi-structured interviews with these teachers and a facility manager were conducted.

Parametric studies were conducted using Radiance for day lighting analysis while Tas Building Designer 9.09e (thermal simulation computer modelling) was used to analyze internal resultant temperatures. Schedule for opening of apertures reflect responses from surveys and interviews and assumes when external dry bulb temperatures (T_o) equal internal temperatures within the comfort zone (T_c) or T_o>T_c, windows are fully open. It should be noted that nocturnal ventilation was not simulated as a ventilation strategy since it is not employed by the teachers for all four classrooms. In addition, Tas Ambiens 9.09e (a 2D computational fluid dynamic programme) used results of surface temperatures obtained from Tas Building Designer 9.09e to compare air patterns and temperature stratification within the four classrooms.

Before Tas simulations could occur, comfort zones were defined for the months of April through October since the case study is concerned with natural ventilation as a passive cooling strategy. Comfort zones were defined using the UC Berkeley Comfort Tool, a programme that includes measures to define detailed comfort zones based on humidity, wind speed, external temperature, mean radiant temperatures, clothing values, and metabolic rates. It allows simultaneous comparisons of PMV/PPD, Auliciems' and Humphreys' neutral temperature, ASHRAE 55-92 standards, and ISO-7730. For purposes of this case study, comfort zones are based on a broad 80 percent acceptance which refers to ±0.85 PMV and 20 percent PPD, considered applicable for naturally ventilated spaces [3].

Metabolic rates are averaged to 1.2 since art studios activities vary between stationary and non-sedentary. Clothing values are based on field observations and survey responses from teachers. Clothing values for the months of April to June and August to October were verified as lightly clad except at 08:00 when average external temperatures are close to 15C. Therefore, the lower limit of comfort uses CLO value of 0.7 while upper limits of comfort use a CLO value of 0.5 (lightly clad). Since average wind speeds for San Rafael are roughly 2.7m/s for these months, a wind speed of 2.0m/s is used to define upper limits of comfort while a 40 percent humidity level is used for both upper and lower limits of comfort.

RESULTS

Art Studio Observations and Survey Results When spot measurements were recorded at 10:30 on June 7th, the Ceramics studio was 2.5K warmer than the drawing studio. Field observations coupled with internal dry bulb spot measurements verify the thermal and visual impact of direct solar radiation along the Eastern façade for the Ceramics Studio. The Ceramics teacher confirmed the exposure along the Eastern façade created direct glare during the hours of 08:00 to 09:00, resulting in the use of blinds in order to block incoming sunlight during these hours (Fig. 1.5 and Fig. 1.6)

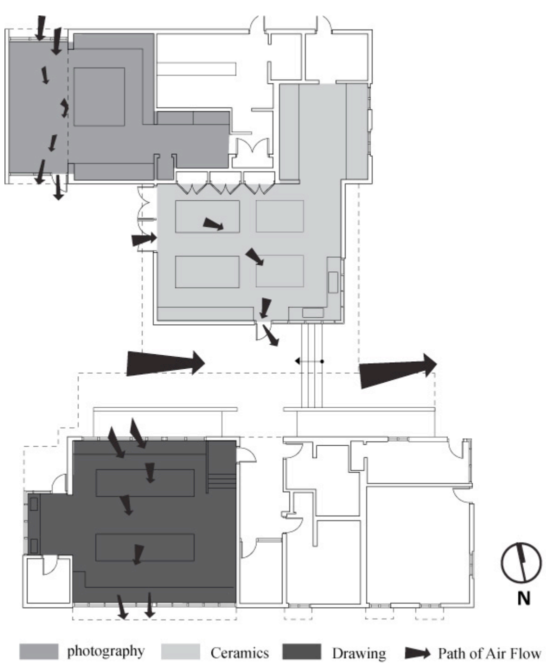


Figure 1.2 : Plan of Art Studios

Even though visual comfort was adversely affected by the direct sunlight along the East façade, the teacher did not explain why the Western glazed Façade was covered with white craft paper as well (Fig. 1.3). Interviews with all three teachers confirmed direct solar radiation was associated with an increase in internal temperature. Therefore, the behavioural adjustment to the Western glazed area in the Ceramics studio might be a reaction to the affects of undesirable solar gains.

Radiance images were produced in order to observe conditions if the glazed areas were uncovered for June 7th at 14:00 (Fig. 1.4). The resulting image revealed that the impact of solar radiation on the space was significant. However, why was the West elevation covered and not the East? It is suggested, since external temperatures are higher after 12:00 and students do not return from lunch until after 13:00, the impact of solar radiation is perceived to affect thermal comfort. Therefore to achieve thermal comfort, occupants adjusted the transparency of the glazed area as to reduce the transmission of direct solar radiation.

Overall, the ceramics teacher was satisfied with the thermal conditions of the space. The teacher verified that there is adequate ventilation throughout the space, but she did not rely on operable windows. Instead, doors were opened on the South and West walls to provide air flow as they were considered easier to operate (Fig. 1.2). To operate the windows, the teacher must reach a latch located three meters above the floor which requires using a pole. As the teacher views this process as cumbersome, operable windows were not used. Fortunately, the West doors are located on the windward side and cross ventilation is achieved. Thermal comfort is perceived as adequate even though the available area of operable apertures is not fully utilized.

Since field measurements spanned two days, thermal conditions of the photography studio could not be compared against the 2D or Ceramics classroom. However, after a discussion with the photography teacher, she claimed her classroom was the warmest. Survey responses confirmed the afternoon hours between 13:00 to 15:00 are "slightly uncomfortable." An interview with the photography teacher also revealed direct solar radiation during the months of May to October is undesirable during these hours. The teacher also acknowledged that the space suffers from a perceived lack of cross ventilation even though inlets along the North elevation are perpendicular to prevailing

Figure 1.3 : Ceramics Studio

Figure 1.4 : Ceramics Studio

Figure 1.5 : Ceramics Studio

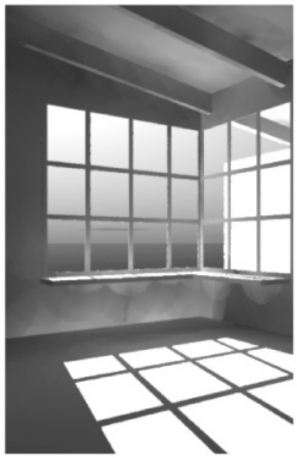


Figure 1.6 : Ceramics Studio

Figure 1.7 : Photography Studio-North Windows

Figure 1.8 : Drawing Studio-North Windows

winds (Fig. 1.2 and 1.7). Therefore, in order to encourage air movement, the teacher must rely on floor fans and lower window blinds in an attempt to reduce the impact of solar radiation on internal temperatures.

Surprisingly, the thermal perception of the 2D studio where operable windows also face North and South was considered satisfactory. Both 1.0 meter overhangs placed over the South facing windows and the presence of large trees along the West elevation reduce solar gains in the afternoon. Since operable windows are placed on either side of students (Fig. 1.2 and 1.8), this strategy allows convection to occur effectively and students are able to take advantage of increased air velocities which increases their acceptance of higher internal temperatures.

PARAMETRIC RESULTS: TAS ANALYSIS

Based on observations from field measurements and survey responses, the data suggests that air flow and direct solar radiation are two critical environmental parameters affecting thermal comfort for a naturally ventilated high school classroom in San Rafael, California. This observation is further supported by the academic dean of the academy who stated "a naturally ventilated classroom is acceptable, only if air movement can be promised." Furthermore, an interview with the Biology teacher, also confirmed that lack of air movement coupled with high internal temperatures is detrimental to student productivity, especially after 13:00 when students return from lunch. Several behavioural adjustments to the classroom were required to achieve thermal comfort in the Biology classroom. Two floor fans directed at students are used to induce a sense of comfort. Also, the impact of direct solar radiation from East windows required the teacher to place tinting film on the glazing and lower internal blinds in an attempt to decrease its effect on internal temperatures.

Therefore, the intention of the parametric studies is to further evaluate the effects of solar radiation and air flow on internal resultant temperatures for day 250, an average warm day in September and throughout the school year. The task includes analysis of not only the cross ventilated art studios, but it also compares the effect of a single sided ventilated general classroom in regards to path of air flow and indoor resultant temperatures. Throughout the analysis, the objective for the investigation also attempts to identify which architectural parameters (e.g. glazing ratios, inlet/outlet locations, and operable window area) affect thermal comfort.

Even though solar gains vary by as much as 2.0kW/m^2 for the three art studios, Tas parametric studies confirm indoor temperatures for all three art studios for day 250 are similar and within the predicted comfort zone (Fig. 1.9). Yet, after 13:00 indoor temperatures are only 1K lower than the upper limits of comfort (29.5C). Since the upper limit of comfort was derived using an input of 2.0m/s, it is suggestive that if velocities are reduced occupant might sense discomfort.

This theory was supported by the photography teacher who perceived her classroom as the warmest and suffers from lack of air movement. Even though the photography studio's equipment gains are high (18 desktop computers), average solar gains for day 250 are almost three times lower than the 2D or Ceramics studio because of reduced glazing area and glazing orientation. If the photography teacher's perception is valid, then the sensation of discomfort is the result of either a lack of air movement due to low pressure differences between the North and South operable windows and/or the path of air flow is not directly related to the occupant. The results support comfort theories which suggest that the sensation of reduced air velocities decrease an occupant's tolerance of increased internal temperatures [1].

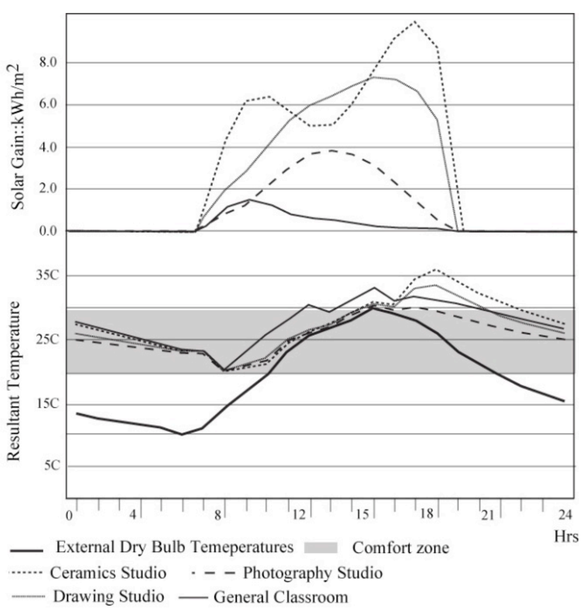


Figure 1.9 : Tas Analysis-Day 250

To further the investigation of natural ventilation's affects on thermal comfort, a single sided ventilated general classroom located on the academy's campus was analyzed. Typically, the classroom is mechanically cooled when internal temperatures reach 24C. Though surveys were not administered to any student or teacher, Tas parametric analyses and Tas Ambiens results are used for comparison. Despite solar gains being four times lower than the art studios and ACH for day 250 were above the minimum 2.0 ACH, Tas confirmed if the standard classroom is subjected to natural ventilation, internal resultant temperatures would fall outside the comfort zone for the hours of 11:00-15:00 (Fig. 1.9).

To further investigate, the same standard classroom is compared against the drawing studio based on computational fluid dynamics. A simplified 2D section was simulated using Tas Ambiens for both spaces (Fig. 2.2 and 2.4). Day 250 was again used to compare indoor resultant temperatures and air flow patterns.

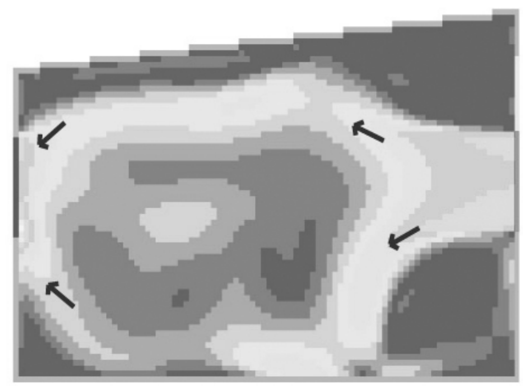


Figure 2.1 : Drawing Studio velocity pattern

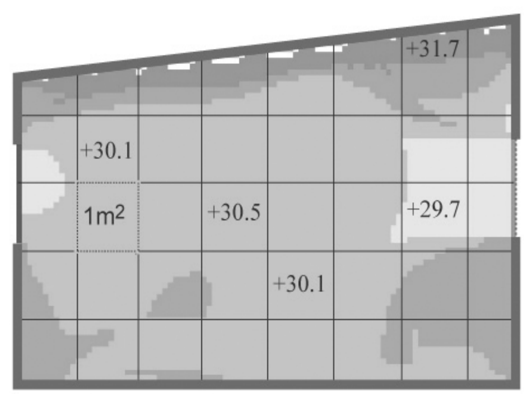


Figure 2.2 : Drawing Studio resultant temperature stratification

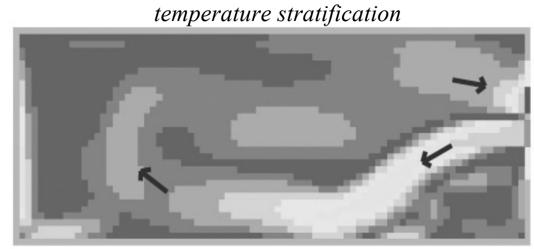


Figure 2.3 : General Classroom velocity pattern

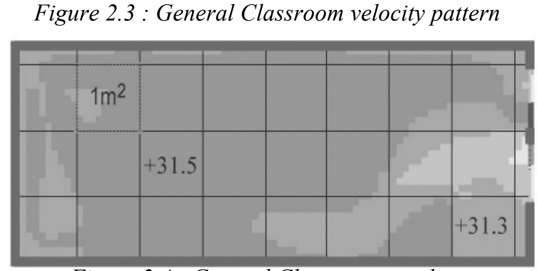
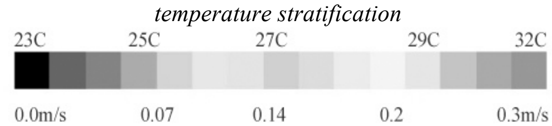


Figure 2.4 : General Classroom resultant temperature stratification



Results from Tas Ambiens further support the idea that single sided ventilation is limited for achieving thermal comfort in a San Rafael classroom. Velocities fall to 0.1m/s, one meter away from the inlet when the simulated inlet speeds are 0.25m/s (Fig. 2.3). Therefore, the path of air flow affects only a portion of the students and reduces the effect of convection. Horizontal stratification is also created since the path of air flow is unable to reduce the surface temperatures of the back wall and ceiling which may contribute to high internal resultant temperatures. The 2D art studio's path of air flow however is clearly defined because of the high pressure created between the inlet and outlet which results in lower indoor resultant temperatures (Fig. 2.1).

CONCLUSION

The intention of the case study was to correlate qualitative and quantitative data in order to highlight which environmental and architectural parameters affect thermal comfort for a naturally ventilated San Rafael classroom. Surveys and interviews confirmed that "overall" the art teachers were happy with thermal conditions of their classrooms, even though indoor resultant temperatures were 0.5K higher than external temperatures for day 250. The correlation between qualitative and quantitative data supports the Adaptive Model [2] that state occupants adapt to internal conditions similar to the external environment. However, results from the case study, suggest this statement should only be applied to spaces which have adequate ventilation and occupants perceive air movement at the working plane.

Although Tas did not reveal adverse affects of solar gains for either the art studios or the standard classroom, interviews and field observations confirmed that direct solar radiation does affect the perception of thermal comfort within a classroom. Tas analyses further suggests the art studio's high volumes decreased the concentration of solar gains per m^3, which relieved the responsibility of natural ventilation to remove internal heat gains. Even though the general classroom and photography studio's solar gains were much lower than the 2D and Ceramics studios, lack of air movement is suggested to be responsible for higher indoor resultant temperatures and a perceived sense of discomfort.

Therefore, both solar radiation and path of air flow are considered to be critical environmental parameters affecting thermal comfort for a naturally ventilated classroom of San Rafael. It is suggested that for natural ventilation to achieve thermal comfort in a San Rafael high school classroom, solar gains should be controlled while the path of air flow should also relate to occupants. In addition, implementation of cross ventilation is recommended not only to encourage high flow rate but to also increase the effective depth of air flow within a space.

Research on naturally ventilated classrooms in San Rafael, California suggests the need for additional field studies involving occupant surveys of teachers and students in order to better inform effective natural ventilation strategies. It is expected that future research and analysis of the parameters affecting thermal comfort in classrooms may benefit passive ventilation strategies for other building typologies with similar highly occupied spaces.

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