MAKING THE CASE FOR HYBRID VENTILATION AND ADAPTIVE COMFORT THEORY IN CANADA: CONCLUSIONS DRAWN FROM A LITERATURE REVIEW

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ABSTRACT

The concept of hybrid ventilation, also referred to as mixed-mode ventilation, has been the subject of investigation of the IEA-ECBCS Annex 35, a research collaborative on Hybrid Ventilation in New and Retrofitted Office Buildings initiated in 1998. Mainly through its detailed case studies, Annex 35 has contributed significantly in broadening the confines of natural ventilation applicability in harsh climates. Although the climatic conditions associated with many pilot study projects are similar in many regards to those found in Canada, transposing Annex 35 exemplars to the Canadian context would prove to be quite exigent. Additional challenges concern regulatory and sustainability issues. This holds true in particular when considering the potential benefits of manually-controlled natural ventilation, conditional to adaptive comfort theory. Through a detailed literature review, this paper re-examines the multiple facets of hybrid ventilation and brings forth a number of conclusions in the light of its application in Canada.

INTRODUCTION

Hybrid ventilation of office and educational buildings has recently attracted a strong following of academics and practitioners alike. The claimed benefits of hybrid ventilation are wide ranging: lower capital costs due to downsizing of HVAC systems, or even their avoidance altogether; enhanced indoor air quality (IAQ); and increased thermal comfort and occupant satisfaction. The authors feel compelled to demarcate these benefits individually, as they are not necessarily related. They also constitute the measuring blocks against which should be assessed future projects integrating hybrid ventilation.

Hybrid Ventilation Definition

Under the auspices of the International Energy Agency’s Implementing Agreement on Energy Conservation in Buildings and Community Systems (IEA-ECBCS), sixteen IEA countries participated in Annex 35. The working definition of hybrid ventilation designates systems that “provide a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of these systems at different times of the day or season of the year” (Heiselberg 2002). Underlying this definition of hybrid ventilation are two chief concepts: first is the recognition that under suitable conditions, natural ventilation may be satisfactory, even preferable, for thermal comfort and indoor air quality (IAQ); and increased thermal comfort and occupant satisfaction. The authors feel compelled to demarcate these benefits individually, as they are not necessarily related. They also constitute the measuring blocks against which should be assessed future projects integrating hybrid ventilation.

Hybrid ventilation principles

The extent to which natural forces are sufficient to meet various comfort and IAQ requirements largely depends on climate, as well as building design and operation. As such, the above definition does not adequately reveal the true diversity of hybrid solutions found in the Annex 35 literature (http://hybvent.civil.auc.dk), and so it has been found necessary to categorized hybrid solutions into three principles (Heiselberg 2002):

1. Natural and mechanical ventilation;
2. Fan-assisted natural ventilation; and
3. Stack- and wind-assisted mechanical ventilation

The natural and mechanical ventilation principle designates dual-mode systems where natural or mechanical ventilation are alternately chosen as the unique ventilation strategy, while the remaining two are based on the complementary use of natural and mechanical forces within common airflow networks.
The distinction between fan-assisted natural ventilation and stack- and wind-assisted mechanical ventilation is made only on the relative importance of natural versus mechanical forces in compensating overall system pressure losses: fan-assisted natural ventilation makes use of back-up mechanical fans strictly to compensate occasional insufficiencies of otherwise autonomous, naturally-driven ventilation systems, while stack- and wind-assisted mechanical ventilation describes low-pressure mechanical ventilation systems that exploit available natural forces to partly offset overall system pressure losses. How would each of these principles fare in Canada? This paper critically explores the previous question by first investigating a limited number of climate-related issues, followed by a concise demonstration of the limited potential of natural forces in lowering system pressure losses. Through a review of thermal comfort models, this paper concludes on the conditional use of adaptive comfort theory as a support for various hybrid ventilation designs in Canadian offices.

CLIMATE SUITABILITY OF HYBRID VENTILATION IN CANADA

It would initially seem fitting to base climate suitability assessments of hybrid ventilation on conditions found in Southern Canada, as an overwhelming majority of Canadians reside along the US border. The Canadian climate remains however quite heterogeneous longitudinally: at one end of the climatic spectrum, South Western British Columbia is blessed with both mild winter and summer conditions, constituting the exception in Canada, while at the other end, the Prairie Provinces are characterized with both extreme winter and summer design conditions; harsh in comparison to those found in Western Europe. It is however the wide-ranging enthalpy conditions found along the Quebec-Windsor corridor which makes this Canadian region the subject of further analysis. This equally applies to the Atlantic Provinces, although to a lesser degree, as well as a considerable part of the US. Basing climate suitability assessment on high (summer) and low (winter) enthalpy conditions is significant as it potentially reduces the number of low-energy passive ventilation solutions. In fact, humidity control in Canadian buildings is generally mandatory, constituting an often sufficient justification for the good practice provision of mechanical humidification/dehumidification, dilution ventilation, enthalpy recovery systems, or any combination of the previous three approaches. This is compounded by the fact that ASHRAE-62 (2001) fresh air rates have been mandatory in Canadian office environments for a number of years (NBC 1995; QCC 2001); rates that are as much as four times greater than those required by many provincial regulations (RRQWE 1999). Such a shift in ventilation rates implies an increase in enthalpy control requirements (e.g. sizing, energy). The provision of mechanical fresh air distribution is also mandatory under the National Building Code of Canada (NBC 1995; QCC 2001), implying that any claimed reductions in capital costs linked to natural or hybrid means of providing ventilation for IAQ are basically groundless. A more detailed review of other regulatory issues facing hybrid ventilation applications in Canada is found in Bourgeois et al. (2002a; 2002b).

Considering that it may be quite cumbersome to add local humidification/dehumidification devices in occupied office environments, natural and mechanical ventilation may only constitute a basis for hybrid ventilation in Canada provided it integrates centrally-controlled technologies for fresh air conditioning, and in particular enthalpy control. This does not rule out natural ventilation and passive climate control in occupied rooms per se, but it would seem to limit their application to space load conditioning, rather than fresh air conditioning. This is in fact the basic rationale underlying the design of dedicated outdoor air systems. On the other hand, fan-assisted natural ventilation and stack- and wind-assisted mechanical ventilation seem at first glance better suited for hybrid ventilation in Canada, as long as enthalpy control equipment is provided somewhere upstream of the airflow path.

HOW NATURAL IS HYBRID?

Adding air conditioning devices, such as heating and cooling coils, energy recovery equipment, filters, etc., along a single airflow path will produce additional pressure losses. As previously stated, it is likely that the installation of a number of such devices may be required within ventilation distribution systems to suit the rigours of the Canadian climate. Any system pressure loss hampers natural airflow. To what extent are available natural forces sufficient to compensate such system pressure losses? Schild (2001) explores this question through weather data analysis of six Norwegian cities (Figure 1).

1 The 2003 public consultations on future technical changes to the National Building Code of Canada have led to a proposal that would allow natural or hybrid schemes in non-domestic buildings, conditional to approval of the provincial, territorial, municipal, etc. authority having jurisdiction (http://www.nationalcodes.ca/consult/tc/nbc/part6/6/index_e.shtml).
Based on these findings, Schild suggests that buildings in Norway must have airflow paths with pressure drops of less than 10 Pa to be truly considered naturally ventilated. As Norway and Canada’s winter conditions are quite similar, Schild's demonstration is useful here in illustrating the limitations of natural ventilation as a driving force within complex airflow networks. Although many Norwegian projects have managed to meet overall system pressure loss targets of ~10 Pa, it is virtually impossible to do so once certain fresh air conditioning processes are introduced. In the case of the Media School, one of the Annex 35 pilot study projects, a run-around heat recovery system generates total pressure losses of ~53 Pa, while filters add another ~20 Pa (Schild 2001). As such, the Media School constitutes a clear case of stack- and wind-assisted mechanical ventilation, appropriate for the Canadian climate. At the same token, this demonstration basically rules out fan-assisted natural ventilation as a working hypothesis for Canada, as back-up fans would constantly be backing-up.

ENERGY SAVINGS RELATED TO STACK- AND WIND-ASSISTED MECHANICAL VENTILATION

The measured total system pressure loss in the Media School is 85 Pa at the design flow rate; a level exceeding available natural pressures, yet extremely low for a mechanically-ventilated building. It would not be contentious to suggest that any potential energy-related benefits derived from exploiting natural forces when faced with such low system pressure losses may be in fact quite low. Even so, the Media School is designed to channel natural airflow through the building – hence becoming hybrid - thereby compensating system pressure losses and eventually, to some extent, fan consumption. Just how effective is further reducing pressure losses in saving energy? Again, Schild demonstrates that the most significant savings in fan energy consumption are achieved by specifying low-pressure drop (low SFP) distribution systems, while the additional gain in energy savings provided by exploiting natural driving forces would be negligible in comparison (Schild 2001).

If natural forces seem to play a marginal role in lowering fan energy consumption of stack- and wind-assisted mechanical ventilation systems, they may on the other hand conflict with the proper operation of the system if not harnessed adequately, as the relative strength of wind and stack effects increases as system pressure drops. Designing stack- and wind-assisted mechanical ventilation based on natural ventilation availability may therefore have more to do with ensuring proper operation of the system than on energy considerations. On the other hand, if matching building operational tasks with the quality of the energy source, or exergy, is a design goal in itself, then hybrid ventilation would seem to be more beneficial. Basing building design on exergy goals would tend to motivate reductions in consumption of electricity (high grade energy) rather than on a low-grade energy task such as space heating. As ventilation fans operate solely on electricity, and inefficiently at that, exergy reductions in fan use rather than heat production would prove to be more substantial. Exergy is

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2 Correspondence from Peter Schild.
highlighted as a contributing factor in the choice of hybrid ventilation of Swedish schools, as part of a national plan to phase out nuclear production of electricity (Wahlström et al. 2002).

**OCCUPANT COMFORT**

Up to this point, the applicability of hybrid ventilation in Canada has been discussed in relation to a number of climate-based regulatory requirements and the resulting role natural forces are left to play in *stack- and wind-assisted mechanical ventilation*, the only year-round scheme that seems applicable in Canada. As previously discussed, these regulatory requirements usually stem from occupant-based concerns (comfort, IAQ, etc.) of operating buildings during the harshest of climatic conditions found in Canada, both in summer and winter. The second part of this paper addresses issues of occupant comfort not covered by the regulatory framework.

**How low can you go?**

*We instinctively depict* natural ventilation schemes as perimeter air entry approaches; an expected propensity as most buildings in the world resort to such techniques for ventilation purposes. It is however dubious to expect comfortable conditions with perimeter air entry approaches during the coldest of conditions, as thermal stratification and draughts would likely occur, even with local heating units. There is some debate over which supply air temperature should be used as a threshold of acceptability. This threshold undoubtedly depends on airflow rates and a number of architectural parameters (window type and placement, room aspect ratios, etc.), but is somewhat more elusive as it varies in time, and among individuals and cultures. It is not the purpose here to determine the threshold value, but rather to establish its existence. Figure 2 illustrates hybrid ventilation principles in the light of their handling of low inlet air temperatures. *Natural and mechanical ventilation* is presented in Figure 2a, with the free-flowing line indicating natural airflow, while a schematic representation of a 100% fresh air mechanical ventilation system is illustrated above the room. Here, there is little theoretical or empirical evidence found in the literature to suggest that inlet temperatures below ~10°C could constitute universally-accepted thresholds, although it is theoretically possible to design for lower values in specific cases, e.g. zones with high internal gains. For the purpose of this discussion, it is reasonable to establish that beyond 0°C, perimeter air entry in *natural* or *free-running* modes would clearly be unacceptable. Beyond that, *natural and mechanical ventilation* resorts to full mechanical ventilation by definition.

![Figure 2](https://example.com/figure2.png)

**Figure 2**

(a) *Natural and mechanical ventilation*; (b) *Fan-assisted natural ventilation*; and (c) *Stack- and wind-assisted mechanical ventilation*.

*Fan-assisted natural ventilation* (Figure 2b) introduces *buffer zones* that *stabilize and condition* outside air before delivery within occupied rooms. The ventilation principle remains naturally-driven peripheral air entry, yet added enhancements such as mechanical preheating compensate for the low inlet temperatures. *Buffer zones* impede on natural airflow by adding pressure losses, as discussed earlier, and the approach must therefore rely upon backup systems such as demand-controlled mechanical extraction. This system introduces a concept of *compromise* in hybrid ventilation: natural airflow autonomy is partially sacrificed for greater stability of inlet temperatures. It is noteworthy that Annex 35 pilot study projects resorting to *fan-assisted natural ventilation* are designed for milder winter conditions than those found in Canada, yet have had notable difficulties in ensuring comfortable conditions, mainly due to draughts, when outside air temperatures are very low (Aggerholm 2002). This is somewhat to be expected in turbulent conditions as small *buffer zones*, e.g. ribbed-pipe
heating units, have response times of several minutes while natural turbulence is best described in
time scales of seconds. In other words, wind turbulence may be pumping outside air in and out of an
aperture without adequate compensation from buffer zones. Again, this supports the assumption that
fan-assisted natural ventilation would seem practically impossible to apply in Canada.

Buffer zones in stack- and wind-assisted mechanical ventilation are further isolated from occupied
zones in order to better stabilize air temperatures and velocities. Yet, as discussed earlier, this
stabilization, although in principle successful, is costly: wind and stack effects no longer constitute the
main driving force that ensures airflow, rather at best, they are channelled in a complementary manner
to reduce overall pressure losses. Compromising natural airflow for greater control is here pushed to
the point where natural driving forces play only a marginal role. Buffer zones introduced in stack- and wind-assisted mechanical ventilation, e.g. culverts or solar chimneys, function well when properly
separated from occupied rooms. This division is critical when considering additional claimed benefits
of natural/hybrid ventilation: although there is considerable evidence to suggest that operable windows
tend to increase occupant satisfaction, the presence of a culvert or a solar chimney, located anywhere
upstream or downstream of the occupied zone, may hardly improve occupant satisfaction, unless one
considers the ethical appreciation of working in a sustainable building as a sign of satisfaction. In fact,
it is virtually impossible from an occupant's perspective to distinguish these solutions from the purely
mechanical ventilation schemes. As there are no direct benefits to the occupant, the end result is that
stack- and wind-assisted mechanical ventilation designs should solely be justified based on economic
or energy/exergy/life cycle costing.

Adaptive comfort theory and hybrid ventilation

The preceding discussion is suggestive that increased occupant satisfaction, an often-cited benefit
of natural/hybrid ventilation, is in fact conditional to occupant-based control strategies. This essentially
rules out expectancies of greater satisfaction in stack- and wind-assisted mechanical ventilation,
unless some local control is given to occupants. There is evidence in the Annex 35 case studies
suggesting that occupants strongly value local control (Aggerholm 2002; Heiselberg 2002). The most
compelling substantiation of this stems from the analysis of the Wilkinson Building in Sydney, Australia
(Rowe et al. 1999). The Wilkinson Building's solution is rather low-tech and laissez-faire in nature, i.e.
occupants have control over windows as well as local air-conditioning (AC) units, which have default
to preferred natural ventilation: although there is considerable evidence to suggest that operable windows
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occupants have control over windows as well as local air-conditioning (AC) units, which have default
controls that require regular, deliberate occupant activation of mechanical cooling. For a cooling-
dominant climate, this has resulted in substantial energy savings while maintaining high levels of
occupant satisfaction (Rowe 2002). This is due to the infrequent use of individual AC units, as a
consequence of a wider tolerance of thermal conditions under free-running modes, i.e. occupants tend
to prefer natural ventilation even when room air temperatures reached ~26°C. Would the same
benefits be available if the Wilkinson Building had been built in Canada? As Sydney has similar
summer design conditions as those in Canada (Bourgeois et al. 2002b), the answer would hopefully
be yes. Yet it is unclear if any occupant-based benefits are available during winter conditions. To get a
clearer picture, greater understanding of the differences between heat balance and adaptive comfort
theory is essential.

The central concept underlying the heat balance model of the body is thermal neutrality, a
physiological state relatively constant among individuals, where external and internal heat gains
counter heat losses to the environment. This equilibrium is assessed through simplified mathematical
models of the human body, involving one or several nodes. The more established models are
Fanger’s single-node model (1972) and Gagge’s two-node model (1986). ASHRAE 55 (1992)
requirements are mainly based on effective temperature contours predicted by Gagge’s two-node
model, while the basis for the ISO 7730 (1994) is Fanger’s main contribution: the now well-established
Predicted Mean Vote/ Percentage People Dissatisfied (PMV/PPD) index, derived from his one-node
model. Both models are compiled from laboratory experiments on human subjects under steady-state
conditions. Although it would be unfair to categorize Gagge’s model strictly as steady-state as it
integrates a temporal variable, Jones (2002) points out that the comfort algorithm was derived from
steady-state data so there is no particular reason to expect it to be correct during transients. The
PMV/PPD index integrates what Fanger considers the six most important variables which influence
thermal comfort. Four are environmental variables: temperature, radiation, air velocity and humidity.
Out of all the possible personal variables, Fanger retained only the following two: metabolic rate and
clothing insulation, possibly because they are unavoidable: every occupant produces internal heat,
and dresses for work!
Although it is generally agreed that the heat and mass exchange within the human body under steady-state conditions may be modelled with acceptable accuracy, data input uncertainty remains significant (Ong 1997; Brager et al. 1998; Jones 2002). Comparison of the Fanger and Gagge models against more complex models also reveal significant discrepancies in comfort predictions under transient conditions (Jones 2002), a strong reminder that both models are derived from steady-state experimentation. Similar discrepancies are observed for draught models, with differences in occupant response to draught varying as a function of activity level, velocity direction and notably personal control of air delivery devices (Griefahn et al. 2001; Toftum 2001). If model uncertainty is so great to the point that determining their value in real life becomes a challenge, how useful then becomes the standard (Mahdavi et al. 1996; Parsons 2001)? How well does the PMV accurately predict the field-based Actual Mean Vote (AMV)? A review of field validation studies of the PMV/PPD index in buildings with HVAC is found in Fanger and Toftum (2001). Haghighat and Donnini (1999) found that 84% of surveyed occupants agreed with the ASHRAE 55 winter comfort zone, yet only 54% were in agreement with the summer comfort zone. Some of the reported discrepancies between the PMV and AMV may be attributed to perceived IAQ (Haghighat et al. 1999; Fanger et al. 2001), a relationship not covered by the standards. This also seems to be the case for other non-thermal factors, such as lighting (Rowe et al. 1995). Potvin (2002) proposes a field-based methodology to assess the interdependencies of environmental stimuli and their effect on environmental satisfaction.

Brager and de Dear (1998) report several studies showing frequent discrepancies between PMV and AMV in actual buildings, especially naturally-ventilated ones in warm climates, where the PMV regularly predicts a warmer thermal sensation than the occupants actually feel (Fanger et al. 2001). As reported by McCartney and Nicol (2001), this phenomena has in fact been observed since the early 1970s (Nicol et al. 1972; Humphreys 1975), when compared results of field studies of thermal comfort in many countries showed that different groups of people were comfortable at remarkably different temperatures. The reasons for the discrepancies are not yet fully understood, but appear to be attributable to an inadequate allowance for people's physiological, psychological and behavioural adaptive responses to the indoor and outdoor climates (Humphreys 1997). This leads us to the second school of thought in matters of thermal comfort in the built environment, adaptive comfort models. Humphreys’ Adaptive Principle: “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Humphreys 1997): the human body no longer constitutes an isolated system to stabilize through heat balance comfort-based control. Adaptive models do not in principle conflict with heat exchange models though, for adjustments to the heat exchange process may be among the actions taken in order to secure comfort. Referring to previous studies in thermal physiology, perception theory and behavioural psychology, Brager and de Dear (1998) define three modes of adaptation: behavioural adjustment, physiological acclimatization; and psychological habituation and expectation. Behavioural adjustment includes conscious or unconscious modifications which modify heat and mass fluxes governing the body’s thermal balance. Three sub-categories are listed: personal adjustment to the surroundings, e.g. drinking cool beverages; technological or environmental adjustment, e.g. opening windows; and cultural adjustment, e.g. adapting dress codes and schedules. Physiological acclimatization includes genetic adaptation and temporal acclimatization. This concept remains strongly disputed by Fanger and Toftum (2001), who argue that thermal responses are relatively constant among individuals. In response to discrepancies between PMV and AMV in naturally-ventilated buildings, they instead suggest that individuals in warm climates expect warm conditions in their work environments, but given a chance would prefer cooler environments. Consequently Fanger and Toftum have introduced their own adaptive model, e: an expectancy correction factor to the PMV index; a function of region, season and indoor environment. Yet there remains clear evidence of physiological adaptation in high temperature environments, e.g. increased perspiration, cardiovascular responses, etc., as presented in Brager and de Dear (2001). Psychological habituation and expectation include cognitive and cultural variables in the thermal perception of, and response to, environmental stress. The adaptive model recognises the potential for a feedback loop where past and current thermal experiences affect current thermal sensations (Brager et al. 1998; Jones 2002). A more detailed review of perception theory in matters of thermal sensation in the built environment is given by Ong and Hawkes (1997; 1997). Banham (1969) also discusses the cultural status associated with air-conditioning, e.g. in homes, offices, cars, etc., which may explain our collective and individual responses to various types of environmental control. Although exercised environmental control is categorized by Brager and de Dear (1998) as a behavioural adjustment, the perception and legibility of personal control fall into the last sub-category (Heschong 1979; Hawkes 1997; Brager et al. 1998). A review of the impact of thermal monotony is also helpful in understanding the role of personal preference in thermal variations (Brager et al. 2001). Overall, there is clearly little
disagreement over the benefits of increasing personal control (Baker et al. 1996; Hawkes 1997; Brager et al. 2001; Fanger et al. 2001).

One of the potential contributions of adaptive comfort models is a reduction of mechanical cooling as a wider tolerance of variations in indoor thermal conditions are observed, when personal environmental control is available (Baker et al. 1996; Brager et al. 2001). One proposed way of reducing cooling loads in naturally-ventilated buildings is to consider a variable comfort temperature instead of a constant set point. Based on an extensive field measurement campaign, the ASHRAE Project 884: Developing an Adaptive Model of Thermal Comfort and Preference (de Dear et al. 1997), de Dear and Brager (1998) have developed a new comfort standard for naturally ventilated buildings to be included as an option to the presently revised ASHRAE 55 Standard, 5.3 Optional method for determining acceptable thermal conditions in naturally conditioned spaces. In essence, it relates the comfort temperature to the monthly mean outdoor air temperature and includes an inferred range of acceptable temperatures based on PMV calculations. Hensen and Centnerova (2001) argue that the time constant of thermal adaptation is more likely to be a few days than a month, and suggest that the daily mean outdoor temperature be used as input for the adaptive comfort standard.

Previous work on adaptive algorithms is reviewed in Brager and de Dear (2001). Based on observations illustrated in Figure 3a, Humphreys (1978) proposed an algorithm relating the comfort to the mean outside air temperature. Later studies reported by McCartney and Nicol (2001) showed that an exponentially-weighted mean outside temperature gives a more accurate relationship. Humphreys and Nicol (1995) found that applying the algorithm as it stood would result in too low internal temperatures when outside temperatures are very cold and a lower temperature limit has been added to the algorithm, as illustrated by the horizontal line in Figure 3b. Supplementary adjustments, including provisions for regional variations, have been added and the updated form of the algorithm is presented in McCartney and Nicol (2001). Provisional results from field studies in two office buildings fitted with the new adaptive control algorithm (one in the UK, the other in Sweden) suggest up to 30% savings in air-conditioning consumption, without affecting the AMV (McCartney et al. 2001). Brager and de Dear (1998) state concerns regarding Humphreys and Nicol’s adaptive control algorithm: although it is derived from field observations of naturally ventilated buildings, its suggested application includes air-conditioned buildings. This indeed seems paradoxical at first, since Humphreys and Nicol suggest different occupant expectations for free-running as opposed to air-conditioned buildings. However, Humphreys and Nicol have stated their preference for mixed-mode or hybrid ventilation through equal opportunities of using locally-controlled AC units or natural ventilation, justifying the use of the adaptive control algorithm with air-conditioning (Humphreys et al. 1998).

One way of integrating adaptive comfort control within hybrid ventilation schemes in Canada would be to link occupant-controlled windows to the building energy management system (BEMS): whenever a window is opened, magnetic contacts are temporarily cut and this signals the BEMS to throttle back local temperature control. A summer scenario: an occupant opens a window when it’s 30°C, zone temperature control consequently throttles back and supplies just enough coolth to stabilize air
temperatures at comfort levels predicted by the adaptive control algorithm. A similar winter scenario: an occupant opens a window when it’s -10°C, zone temperature control consequently throttles back so climate control is basically free-running; occupant closes window if warmer conditions are preferred. Windows are now designed here as user-friendly adaptive environmental switches. This strategy clearly relies on local control of heating and cooling, such as provided through local heat pumps on a water loop. On the other hand, the application of the adaptive control algorithm would be challenging for centrally-controlled heating and cooling systems. Yet a combination of a dedicated outdoor air approach to fresh air delivery and local occupant-controlled heating and cooling units, similar to the Wilkinson Building approach, would offer a number of adaptive opportunities to occupants, while forgoing the adaptive control algorithm altogether. Room temperature could instead float according to occupant preferential use of windows and local climate control units. The adaptive control algorithm would instead be useful for design purposes in an energy simulation context, by predicting when individual occupants would typically switch from various control schemes.

In summary, there is evidence to suggest that integrating adaptive comfort control within hybrid ventilation solutions would in theory encourage energy savings in summer, but there is little support for this in winter. Any physiological acclimatization would most likely equal thermal stress and thus would acquire a negative connotation. To some extent, the same may be said for psychological habituation: the appreciation of working in a historic building may counter the occasional rubbing of hands on a cold winter day, but one intentionally strives by design to avoid any trade-offs in that sense. In fact, the literature review shows that there is little evidence to suggest that wider tolerance of thermal conditions is expected below ~10°C. This value actually constitutes the applicability threshold of the ASHRAE 55 adaptive comfort model (Brager et al. 2001). This is also clearly supported by Haghighat and Donnini (1999) who show that there is little evidence of general occupant dissatisfaction to centrally-controlled uniform environments in winter, specifically in Canadian office environments. This supports the applicability of both the ASHRAE 55 and the ISO 7730 standards for centrally-controlled uniform work environments. Figures 3a and 3b even suggest higher expectancies in indoor temperatures during winter, as measured comfort temperatures seem to hover at ~23°C instead of ~21-22°C, suggesting a potential increase in heating demand if adaptive comfort models are used in winter instead of the ASHRAE 55 or ISO 7730 standards (Hensen et al. 2001).

CONCLUSION

This paper presents a critical review of hybrid ventilation and adaptive comfort theory in relation to Canadian office environments. Addressing the relevance of a number of claimed benefits linked to both approaches, a number of key principles to consider are suggested:

1. Climate-based regulatory and comfort issues virtually rule out fan-assisted natural ventilation as a year-round solution for offices along the Quebec-Windsor corridor, leaving stack- and wind-assisted mechanical ventilation, or full mechanical distribution under natural and mechanical natural ventilation schemes, as the only acceptable modes of climate control in winter;

2. In stack- and wind-assisted mechanical ventilation, the only year-round, common airflow path scheme applicable in Canada, natural forces can only partly compensate system pressure losses. It thus becomes semantically challenging to distinguish good stack- and wind-assisted mechanical ventilation designs from good low-pressure mechanical ventilation schemes. Choosing either should solely be based on economic and/or energy/exergy/life-cycle costing analysis, rather than on false expectations of increased occupant satisfaction. Additional reductions in cooling have little to do with ventilation, but rather on proper control of solar and internal gains, a solution common to both hybrid and non-hybrid solutions;

3. Adaptive comfort models are in principle only applicable when occupants have access to adaptive opportunities, namely operable windows, and are restricted to warm conditions, i.e. above ~10°C. Any potential energy savings resulting from adaptive comfort control would therefore be confined to mechanical cooling, a fact worth considering in a heating-dominant climate;

4. There is a general consensus over the benefits of providing occupant-based climate-control to address individual thermal preferences in winter and summer, independent of the comfort model;

5. Combining dedicated outdoor air approaches strictly for fresh air conditioning and delivery (possibly a stack- and wind-assisted mechanical ventilation scheme) with a local occupant-based climate-control approach to zone heating and cooling (natural and artificial) would likely constitute the most compatible and robust strategy to hybrid ventilation and adaptive comfort in Canada.
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