Thermal comfort and risk of draught with natural ventilation - assessment methods, experiences and solutions

Jannick Roth[*1], Per Heiselberg[*2], Chen Zhang[*2]

1 WindowMaster International A/S
Skelstedet 13
2950 Vedbæk, Denmark
**Corresponding author: jkr.dk@windowmaster.com*

2 Aalborg University
Thomas Manns vej 23
9220 Aalborg, Denmark

ABSTRACT

The majority of research and hence the assessment methods and tools for thermal comfort assessment of ventilation systems are not based on findings for natural ventilation solutions and do not take into account the specific characteristics of natural ventilation. This has created a lack of suitable methods for the assessment and performance evaluation of natural ventilation. This paper will focus on the evaluation of assessment methods related to estimating the risk of draught for natural ventilation systems. The key objectives and questions to be addressed are: 1) Is the current Draught Rate method suitable for the evaluation of natural ventilation and are there currently other more appropriate methods for assessing the risk of draught? 2) What are the main findings and experiences until now and to what extent can we use these? Furthermore, examples of solutions for ensuring thermal comfort in cold periods will be presented and their performance discussed based on different performance assessment methods used. This paper will conclude on the status of natural ventilation comfort performance assessment in relation to thermal comfort and the risk of draught.

KEYWORDS

Natural ventilation, air movement, draught (draft) risk, Thermal comfort, window opening.

1 INTRODUCTION

The usage of natural ventilation is now, more than ever, being pushed forward due to agendas like: reduction in CO_2 emissions including operational energy and materials as well as resiliency including focus on buildings' ability to e.g., increase the airflow rates during peak load periods and unexpected events. However, there is a risk that the current assessment methods are overestimating the risk of draught for natural ventilation systems. This is typically the case when openings directly to the outside are being used for ventilation and the temperature difference between inside and outside is more than 5K.

Draught is, in the literature and standards, defined as “the unwanted local cooling of the body caused by air movement” (Fanger 1977; ASHRAE 55; EN/TR 16798-2). Several studies have been conducted to address the main factors influencing the risk of draught like air temperature, velocity, air turbulence, exposed body parts, clothing insulation level, and overall thermal comfort (Fanger 1977; Fanger et al 1988; Houghten et al 1938; McIntyre 1979; Toftum et al 2003; Schiavon et al 2016; Liu et al 2017).

This paper evaluates the risk of draught for natural ventilation systems and compares different assessment methods used in current standards. The paper first includes a description of different draught assessment methods, then describes experiences and findings related to airflow patterns, temperatures and velocities in naturally ventilated spaces and finally compares the estimated risk of draught by different methods and suggests technical solutions to reduce it.

2 ASSESSMENT METHODS

2.1 Overall

Most of the research conducted on thermal comfort and assessment of the draught risk of ventilation systems focuses on mechanical ventilation solutions and fails to consider the specific characteristics of natural ventilation. This has created a lack of suitable methods for assessment and evaluation of the draught risk performance of natural ventilation.

Key aspects and considerations when evaluating a natural ventilation system in terms of draught, include:

- High degree of user control: influence on the perceived indoor environmental quality.
- Visual openings/ventilation: this might lead to greater acceptance.
- Air distribution patterns: displacement or mixing depending on driving forces.
- Operation strategy: continuous or intermittent operation.

It should be noted that fulfilling the given criteria of thermal comfort and draught does not mean 100% acceptance of all occupants. Individual preferences and differences in activity and clothing levels make it difficult to satisfy everyone in space. Individual control of the thermal environment or individual adaptation (clothing, activity) increases the level of acceptance.

2.2 Risk of draught

The risk of draught is expressed in various present thermal comfort standards ISO 7730:2005, EN 16798-1:2019 and ASHRAE 55-2020. EN 16798-1 and ISO 7730 are both based on the widely used and recognised model for assessing the risk of draught developed by Fanger et al (1988). The risk of draught is evaluated by the draught rate (DR), which expresses the percentage of people dissatisfied due to draught. DR is not only determined by the local air velocity, but also influenced by air temperature and turbulence intensity, as presented in Eq. (1).

$$DR = (34 - t_{a,l})(\bar{v}_{a,l} - 0.05)^{0.62}(0.37 \cdot \bar{v}_{a,l} \cdot T_u + 3.14) \tag{1}$$

Where:
DR is the predicted percentage dissatisfied, %
$t_{a,l}$ *is the local air temperature, in degrees Celsius, 20 °C to 26 °C;*
$\bar{v}_{a,l}$ *is the local mean air velocity, in metres per second, < 0,5 m/s;*
T_u *is the local turbulence intensity, in percent, 10 % to 60 %*

This model applies to people with sedentary activity and with a neutral thermal sensation for the whole body. In addition, the model is designed to predict the draught rate at the neck level, and an overestimation is expected when predicting the draught at the arm or feet level. The expected overestimation of draught at arm and feet level by Fanger et al (1988) is illustrated in Figure 1, where the dissatisfaction with draught modelled by Eq. (1) developed for neck level is compared with the measured number of dissatisfied with draught rate at feet level. There is an almost linear correlation, meaning that it is possible based on the figure and measurements to calculate both the expected draught levels at the neck, arm and feet level.

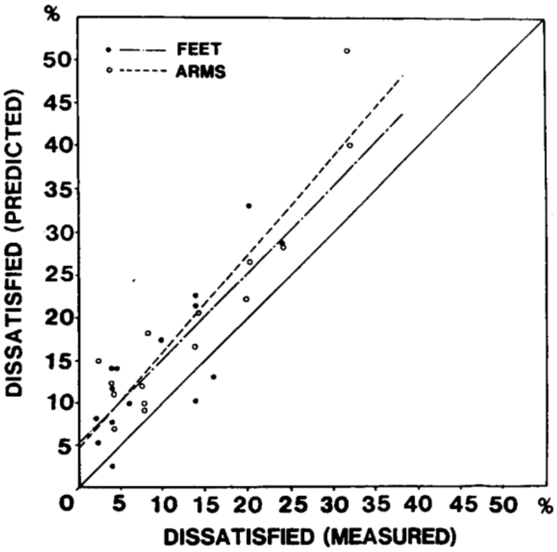


Figure 1. Comparison of predicted and measured percentages of draught risk for arms and feet (Fanger et al, 1988).

Based on a recent study from Berkeley (Schiavon et al 2016; Liu et al 2017) a new draught risk assessment method has been added in the recent ASHRAE 55-2020. The method assesses the risk of draught at the ankle region, 0.1m above floor level, valid for clo < 0.7 and met < 1.3. This method can be applied in buildings with thermally stratified systems, such as displacement ventilation and underfloor air distribution. The maximum air speed at ankle level can be derived using Eq. 2:

$$V_{ankle} < 0.35 \cdot TS + 0.39 \quad (2)$$

Where:

V_{ankle} *air speed at 0.1m above floor, m/s*

TS whole body thermal sensation; Equal to PMV calculated using the input air temperature and speed averaged over two heights: 0.6m and 1.1m for seated occupants and 1.1m and 1.7m for standing occupants.

Based on eq. (2) a maximum air speed of 0.39 m/s can be applied if the whole-body thermal sensation is neutral (TS=0). The online CBE Thermal Comfort Tool (Tartarini et al., 2020) can be used to assess the risk of draught at the ankle level.

3 FINDINGS AND EXPERIENCES

3.1 Assessing the airflow pattern

Openings for natural ventilation are often placed either close to the ceiling or close to the occupied zone, and the characteristics of the airflow from the openings play a crucial role in ensuring comfortable conditions. Hence, one important aspect when evaluating and improving the concept (e.g. due to draught) is to be aware of the different air distribution regimes that can occur with the chosen design. Figure 2 shows the typical air distribution conditions in a room with high positioned openings. The airflow will assume one of three primary patterns and will be dependent on the opening area as well as indoor/outdoor temperature and pressure difference.

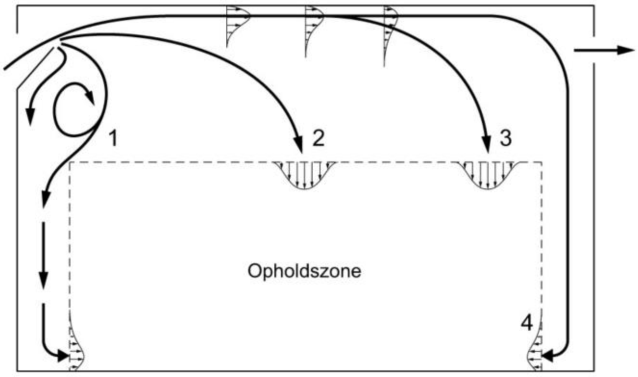


Figure 2. Typical air distribution conditions in a room with high-positioned openings (Heiselberg, 2006)

Table 1 explains when the air distribution conditions shown in Figure 2 typically occur. This explanation is found in Heiselberg (2006), which is based on several studies (Bjorn et al., 2000; Heiselberg et al., 2001 and 2002).

Table 1. Explanation of air distribution conditions in a room with high-positioned openings (Heiselberg, 2006).

Flow regime	Typically occurring	Flow pattern
1	Small driving forces (0.2 – 0.4 Pa) or low outdoor temperature supply air (high indoor/outdoor temperature difference).	Air distribution in the room will follow the displacement principle and the draught risk will be highest along the floor.
2 & 3	Driving forces ($\Delta p > 4\text{-}6$ Pa) or higher outdoor temperatures ($\Delta t < 5$ K)	Air distribution in the room will act as a thermal jet and traditional jet theory can be used to predict airflow path and draught risk will typically be highest at neck level.
4	For bottom-hung windows close to the ceiling during warmer outdoor temperatures	Air distribution in the room will act as an isothermal jet.

For low-positioned openings in the façade the aim is to distribute air to the room according to the displacement principle to achieve a high ventilation efficiency and the highest draught risk will always be close to the floor.

3.2 Risk of draught evaluation for natural ventilation

Several laboratory measurements and Computational Fluid Dynamic (CFD) simulations were carried out during the research project ‘‘Natural cooling and ventilation through diffuse ceiling supply and thermally activated building constructions” (Zhang, C. et al, 2015 and 2016). The measurement and assessment of draught risk included both a natural ventilation setup with high positioned façade openings and a setup based on diffuse ceiling supply.

Figure 3 illustrates a 2-person office room test setup and measuring positions in the room. Three bottom-hung high level inward façade openings with a dimension of 350x800mm (HxW) was located about 2.4m above floor level. The test included two heat load scenarios of around 30 W/m^2 and 60 W/m2 with an air change rate of 2 (85,5 m^3/h) and 4 (171 m^3/h), respectively. Air was continuously being supplied to the room. Temperature difference (indoor/outdoor air) varied from 0-32K.

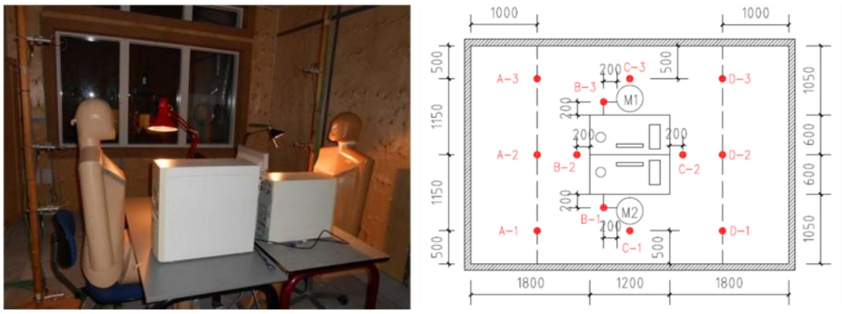


Figure 3. Test setup, measuring positions in the room and on the columns (Zhang, C. et al, 2015).

Extended results from the work are displayed in this paper, by going even further in depth with the results for the natural ventilation with high level façade openings compared to earlier shown results. It should be noted that the turbulence intensity in the study was set to 40% - for some tests some could argue to use 20% instead.

Gunnar et al (2017) conducted several experiments in a thermally insulated test room and assessed the risk of draught in a room with a high-level façade opening with a supply air flow rate of 14 and 29 l/s with an inlet temperature of around 0 ºC. It should be noted that the turbulence intensity in the study was selected to be 10%, however for the current study the draught rate was re-calculated based on a turbulence intensity of 20% in order to compare results from the different studies. Figure 4 shows the test setup.

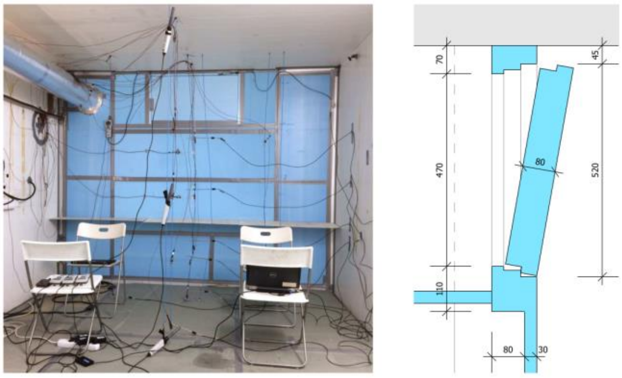


Figure 1: view inside the test room (left), section of the vent (right)

Figure 4. View inside the test room (left) and section of the opening vent (right) (Gunnar et al, 2017).

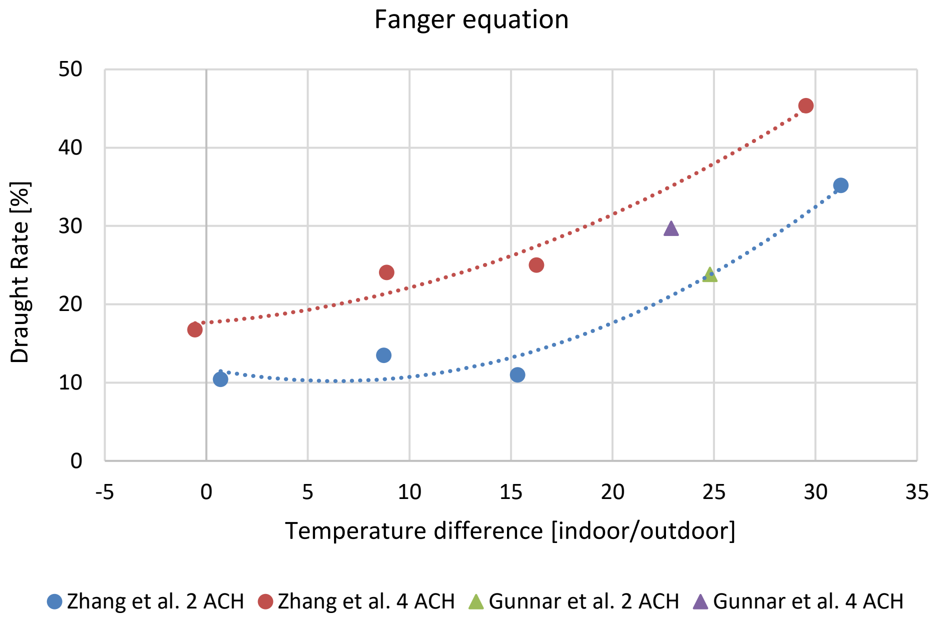


Figure 5. Calculated draught rates using Fanger's equation.

The maximum draught rates in both studies are calculated by different assessment methods as introduced in Section 2.2. Figure 5 illustrates the draught rates calculated by Fanger's equation (eq. 1). It shows, as expected, that the risk of draught increases as the temperature differences between indoor and outdoor increases. A draught rate < 20% can be achieved at a temperature difference below 6 K and 22K for 4 and 2 air changes, respectively.

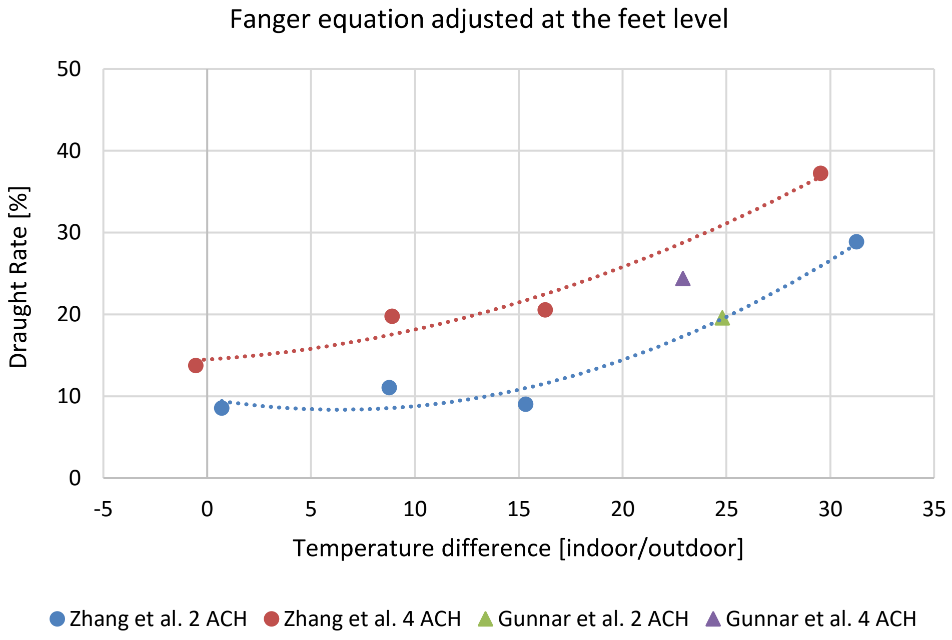


Figure 6. Calculated draught rates using adjusted Fanger's equation at the feet level.

Figure 6 shows the adjusted draught rates at the feet level based on Fanger's equation. A correlation coefficient of 0.82 is applied to the feet level, as shown in Figure 1. The reason for the lower draught rate at the feet level is that people are less draught sensitive at the feet than the head. In addition, clothing plays an important role. Normally, people have their feet and ankles covered, and the clothing layer will damp the thermal impact on the skin. The Fanger's equation is designed to predict the draught rate at the neck level, and an overestimation is expected when predicting the draught at ankle level.

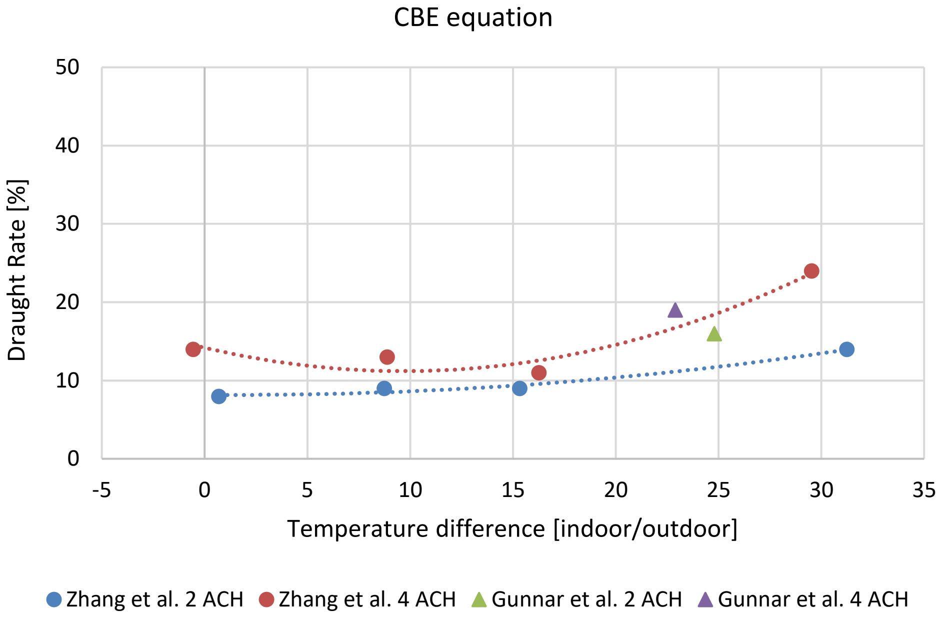


Figure 7. Calculated draught rates using CBE equation.

Figure 7 presents the draught rates calculated by the CBE equation, with an assumption of relative humidity 50%, clothing level 0.7 clo and metabolic rate 1.2 met. It could be observed that the draught rates calculated by the CBE method are much lower compared to the other two methods. The highest DR is 24% by CBE method, while the values by Fanger's method and adjusted Fanger's method are 45% and 37%, respectively.

This is because CBE method considers both whole body thermal sensation and air speed at ankles as key parameters affecting draught, while Fanger's method assumes people with a neutral thermal sensation and focuses on the importance of local air conditions, such as air speed, temperature, and turbulence intensity.

4 SOLUTIONS COPING WITH DRAUGHT

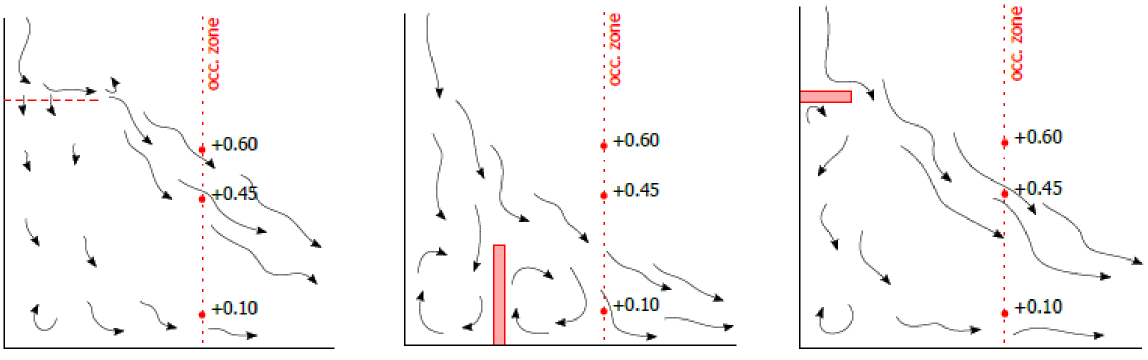
There are different design solutions that can be used in order to minimise the risk of draught. Table 2 gives design recommendations depending on the specific goal.

Table 2. Design options to reduce draught risk for natural ventilation.

Goal	Solution
Higher air inlet temperature	▪ Double skin façade solutions
Lowered air velocities	▪ Diffuse ceiling supply ▪ Obstacles e.g. a perforated plate like a window sill. ▪ Radiator below incoming air.
Higher air inlet temperature and lowered air velocities	▪ Diffuse ceiling supply

Zhang et al. (2015 and 2016) developed a novel air distribution concept for air intake from the façade at the ceiling level. Outdoor air is supplied to the space between the suspended ceiling and the ceiling slab and supplied to the room through diffuse ceiling panels. Due to the large inlet opening area, the ventilated air is supplied into the room with very low velocity. The measured results indicated that even at supply air temperatures of -7 °C, the draught rate was below 10 %, as shown in Figure 8.

Gunnar et al (2017) investigated if different types of obstacles, below a high-level opening, could minimize the risk of draught. Two different windowsills were tested one was solid and the other was a perforated plate, both were located 75cm above floor level. A 30cm high vertical shelf placed on the floor approx. 30 cm from the outer wall was also tested to see if this could minimize the risk of draught. Figure 8 illustrates the flow patterns with different types of obstacles. Figure 9 shows that by introducing different obstacles below the façade openings can potentially minimise the draught rate by more than 10% points.



Obstacle 1 Obstacle 2 Obstacle 3

Figure 8. Qualitative visualization of the flow pattern with different types of obstacles (Gunnar et al, 2017)

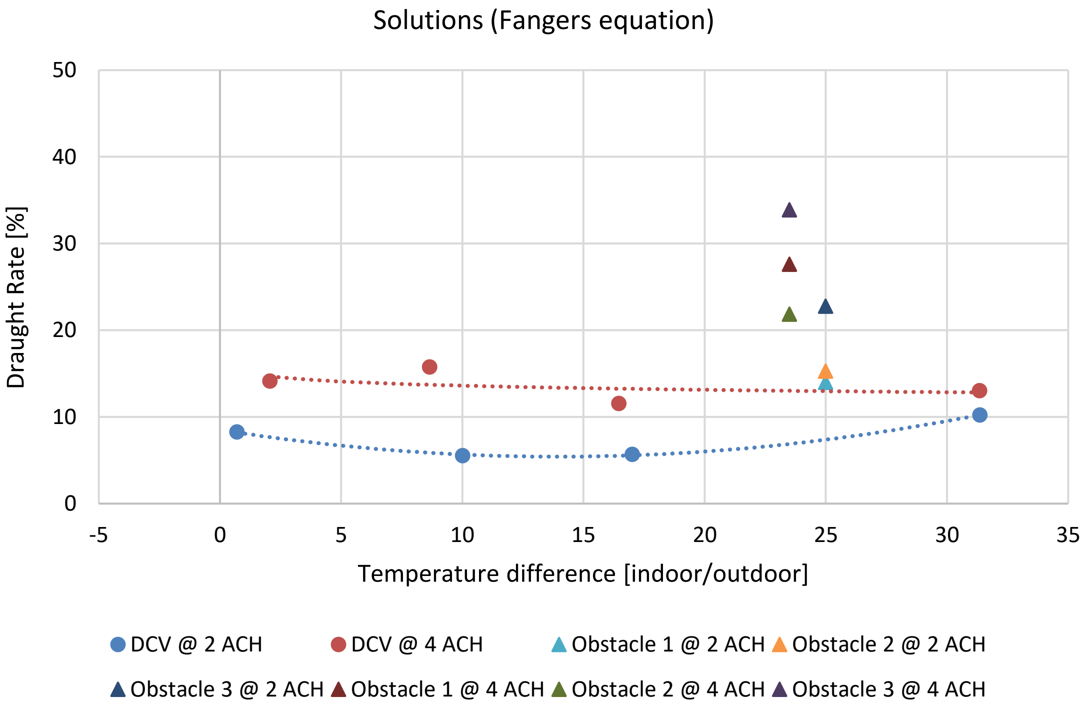


Figure 9. Risk of draught using diffuse ceiling supply (DCV) and various obstacles with Fanger's equation

5 DISSUSSION AND CONCLUSIONS

This study compared various methods proposed in current standards and literature for assessing draught rate, including Fanger's method, Fanger's method adjusted for draught risk at feet level and the CBE method. The results indicate significant deviations in predicted

draught rate when different methods are utilized. The commonly used Fanger's method tends to overestimate the draught risk associated with natural ventilation, especially in systems using displacement air distribution patterns. Further investigation is needed to identify the most suitable method for evaluating draught risk in natural ventilation systems.
On the other hand, elevated air speeds do not always result in unpleasant draught. In some situations, increased air speed could enhance perceived comfort. Whether air movements lead to draught, or enhance perceived comfort depends on factors like activity level, thermal environment, overall thermal sensation, clothing, ability to personally adjust air velocities etc. Further studies are recommended to explore methods of increasing personal control on the assessment of draught risk of natural ventilation.

6 ACKNOWLEDGEMENTS

This work was supported by the project: Hybridene – Optimal hybrid ventilasjon I fremtidens bygg, financed by The Research Council of Norway (project nr. 327591).

7 REFERENCES

ISO 7730 (2005). Moderate thermal environments. Determination of the PMV and PPD indicies and specification of the conditions for thermal comfort.

EN 16798-1 (2019) Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6

ASHRAE Standard 55 (2020). Thermal environmental conditions for human occupancy

Fanger PO (1977) Local discomfort to the human body caused by non-uniform thermal environments. Annals of Occupational Hygiene, 20, 285-291.

Fanger PO, Melikov AK, Hanzawa H et al (1988) Air turbulence and sensation of draught. Energy and Buildings, 12, 21-39

Houghten F, Gutberlet C, Witkowski E (1938) Draft temperatures and velocities in relation to skin temperature and feeling of warmth. ASHVE Transactions, 44, 289-308.

Toftum J, Melikov A, Tynel A et al (2003) Human response to air movement—Evaluation of ASHRAE's draft criteria (RP-843). HVAC&R Research, 9, 187-202.

McIntyre, 1979. D.A. McIntyre. The effect of air movement on thermal comfort and sensation. P.O. Fanger, O. Valbjørn (Eds.), Indoor Climate, Danish Building Research Institute, Copenhagen, 1979, pp. 541-560.

Schiavon, Stefano, Donghyun Rim, Wilmer Pasut, and William W Nazaroff (2016). "Sensation of Draft at Uncovered Ankles for Women Exposed to Displacement Ventilation and Underfloor Air Distribution Systems." Building and Environment 96 (February 1, 2016): 228–36.

Liu, Shichao, Stefano Schiavon, Alan Kabanshi, and William Nazaroff (2017). "Predicted Percentage Dissatisfied with Ankle Draft."Indoor Air, January 2017.

Tartarini, F., Schiavon, S., Cheung, T., Hoyt, T.(2020). CBE Thermal Comfort Tool : online tool for thermal comfort calculations and visualizations. SoftwareX 12, 100563. https://doi.org/10.1016/j.softx.2020.100563

Heiselberg, P. (2006). Design of Natural and Hybrid Ventilation. Department of Civil Engineering, Aalborg University. DCE Lecture notes No. 5

Heiselberg, P., Bjørn, E. (2002). Impact of Open Windows on Room Air Flow and Thermal Comfort. International Journal of Ventilation, Vol 1, No. 2, pp 91-100, October 2002.

Heiselberg, P., Svidt, K., Nielsen, P.V (2001). Characteristics of airflow from open windows. Building and Environment, 36 (2001), pp 859-869.

Bjorn, E., Jensen, J., Larsen, J., Nielsen, P.V. and Heiselberg, P. (2000). Improvement of thermal comfort in a naturally ventilated office. Proceedings of the 21st AIVC Conference, Den Haag, The Netherlands, September 22-25 (CP21). Air Infiltration and Ventilation Centre, AIVC.

Zhang, C., Heiselberg, P. K., Pomianowski, M., Yu, T., & Jensen, R. L. (2015). Experimental study of diffuse ceiling ventilation coupled with a thermally activated building construction in an office room. Energy and Buildings, 105, 60–70. https://doi.org/10.1016/j.enbuild.2015.07.048

Zhang, C., Yu, T., Heiselberg, P. K., Pomianowski, M. Z., & Nielsen, P. V. (2016). Diffuse Ceiling Ventilation: design guide. Department of Civil Engineering, Aalborg University. DCE Technical Reports No. 217

Gunner, M., Justo-Alonso M., Dokka TH. (2017), Façade Improvements to Avoid Draught in Cold Climates – Laboratory Measurements. 38th AIVC Conference "Ventilating healthy low-energy buildings", Nottingham, UK, 13-14 September 2017