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TNO report

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Adaptive Air Curtains Public Report

CFD simulations and experiments

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Management Samenvatting

Voor makkelijke toegang tot winkels of magazijnen wordt vaak een open deuropening gebruikt. Als het buiten kouder is dan binnen levert dat aanzienlijke warmteverliezen, die echter door toepassing van een luchtgordijn boven de deuropening aanzienlijk kunnen worden verminderd.

De prestatie van een luchtgordijn wordt uitgedrukt in de scheidingsefficiëntie (Climate Separation Efficiency -CSE), de mate waarin een luchtgordijn warmteverliezen vermindert in vergelijking met een open deuropening (dus als het luchtgordijn is uitgeschakeld). Dit project, uitgevoerd door TNO en fabrikant van luchtgordijnen Biddle, had tot doel de prestatie van luchtgordijnen waar mogelijk te verbeteren.

State-of-the-art van parameters die de prestatie bepalen

Een literatuuronderzoek is uitgevoerd naar parameters die de prestatie van een luchtgordijn bepalen. Het cruciale effect dat moet worden bereikt is dat de lucht die door het luchtgordijn naar beneden wordt geblazen, de vloer bereikt. Wanneer de luchtstroom te lage snelheid heeft (in feite: impuls), zal deze de vloer niet bereiken, met als gevolg dat koude lucht van buiten over de vloer naar binnen dringt. Ook als de luchtstroom met te hoge snelheid de vloer raakt, blijken binnen- en buitenklimaat minder efficiënt te worden gescheiden dan bij de optimale luchtsnelheid.

Het gedrag van de luchtstroom kan worden beschreven met het afbuigingsgetal (Deflection modulus - D_m), een dimensieloos getal dat de verhouding aangeeft van de impuls van de luchtstroom uit het luchtgordijnen en de dwarskrachten ten gevolge van dichtheidsverschillen over de deuropening.

Naast geometrische parameters zoals de breedte en de hoogte van de deuropening (die in een specifieke toepassing vastliggen), zijn de belangrijkste parameters die D_m bepalen:

- Temperaturen van binnenlucht, buitenlucht en uitgeblazen lucht uit het gordijn,
- Snelheid van uitgeblazen lucht,
- Hoek waarmee de lucht wordt uitgeblazen en
- Breedte van de uitstroomopening

Eindgebruikersbehoeften en bijbehorende Key Performance Indicators (KPI's),

In workshops met klanten van Biddle bleek dat het thermische comfort voor kassières dichtbij de ingang een belangrijk aandachtspunt is. Het comfort wordt negatief beïnvloed door tocht ten gevolge van de luchtstromingen rond de deuropening. Parameters die het comfort verlagen, zijn onder meer:

- Temperatuur van de tochtstroom,
- Exfiltratie door hoger gelegen openingen boven de deuropening, typisch voor een gebouw dat niet helemaal luchtdicht is.
- Menselijk verkeer door de deuropening (dat wil zeggen mensen die door het luchtgordijn lopen).

Om het comfortverlies door tocht te beperken, wordt de lucht uit het luchtgordijn vaak voorverwarmd tot maximaal 35°C.

Operationeel bereik van relevante parameters

Uit een overzicht van de literatuur (Hendriksen, 2017) interviews met klanten van Biddle en rekening houdend met de resultaten van voorgaand onderzoek, is een aantal parameters geselecteerd voor verder onderzoek in dit project. Deze parameters en hun bereik zijn samengevat in onderstaande tabel.

Parameter	**Bereik**	**Opmerkingen**
Temperatuur binnenlucht	21°C	Vaste waarde, gebruikelijke binnentemperatuur in winkels
Temperatuur buitenlucht	0-15°C	Gebruikelijke buitentemperaturen in het Nederlandse stookseizoen
Inblaastemperatuur lucht	20-35°C	Gelijk aan binnentemperatuur als inblaaslucht niet wordt verwarmd, max waarde bepaald door comfort
Uitblaassnelheid	1-5m/s	Typisch voor Biddle Comfort luchtgordijnen
Uitblaashoek	0-10 graden	Vermeld in de literatuur
Breedte uitblaasopening	4-6cm	Typisch voor Biddle Comfort luchtgordijnen
Neutrale hoogte in verband met openingen boven luchtgordijn	60-80%	70% werd typisch gemeten door Biddle in een praktische situatie
Mensen die door het luchtgordijn lopen	1-60 per minute	Door begrotingsbeperkingen is er maar één experiment uitgevoerd (geen CFD)

Beschrijving van een 'base case' inclusief relevante geometrieën

De 'base case' in dit onderzoek wordt weergegeven door de testopstelling in het TNO MEC lab, bestaande uit een Biddle Comfort luchtgordijn dat boven een 2m brede en 2.3m hoge deuropening is gemonteerd. Dit is de 'full scale' opstelling.

Gezien het belang van het effect van openingen boven de deur, is de deuropening in het TNO-lab verlaagd tot een hoogte van 1m (met dezelfde breedte van 2m) en voorzien van extra openingen daarboven. Deze opstelling heet de 'verlaagde opening'. Hierin zijn naast de grootte van de opening boven de deur ook de uitblaashoek van de luchtstroom van het luchtgordijn gevarieerd. De experimentele opstellingen zijn meer gedetailleerd beschreven in hoofdstuk 3.

Daarnaast is een CFD-model gemaakt van zowel de 'full-scale' als 'verlaagde opening' opstelling. Het CFD-model is in detail beschreven in hoofdstuk 4.

Focus van het onderzoek

Het effect van de parameters in bovenstaande tabel op de prestatie is beoordeeld door het bepalen van de scheidingsefficiëntie CSE, telkens bij een aantal uitblaassnelheden (of ventilatorsnelheden). Experimentele resultaten zijn vergeleken met de CFD-berekeningen.

Momenteel controleert Biddle een beperkt aantal parameters (zoals de uitlaatsnelheid) om een optimale prestatie van hun luchtgordijnen te behalen. Het doel van de huidige studie is inzicht te krijgen in de effecten van bovenstaande parameters, waardoor een verbeterd besturingsalgoritme kan worden bepaald, waarbij de prestatie kan worden geoptimaliseerd onder een breder scala van gebruiksomstandigheden.

Conclusies

De belangrijkste conclusies die uit de resultaten kunnen worden getrokken, zijn de volgende:

- In onze experimenten en CFD-simulaties zijn grote hoeveelheden gegevens verzameld, zoals snelheden en temperaturen van luchtstromen onder een breed scala van gebruiksomstandigheden. De meest bruikbare grootheid om de resultaten in te condenseren en een vergelijking tussen experiment en CFD-simulatie mogelijk te maken, bleek de scheidingsefficiëntie CSE te zijn.
- Bij het vergelijken van CSE's is in het algemeen een goede overeenkomst tussen experimenten en CFD-simulaties gevonden. Dit laat zien dat ons CFD-model een zeer bruikbaar instrument is om de prestaties van een luchtgordijn mee te bepalen onder een scala van gebruiksomstandigheden.
- Helaas duurde het uitvoeren van een CFD-scenario veel langer dan verwacht (meestal 2 dagen) door het vereiste detail van het model en de dynamiek van de stroomprocessen die plaatsvinden. Bijgevolg is het aantal CFD-simulaties beperkt gebleven door de beschikbare tijd en budget.
- Bij het veranderen van de temperatuur van de koude ruimte (‘buiten’) bij gelijkblijvende temperatuur van de warme ruimte (’binnen’), bleek de maximale CSE in de orde van 70% -80% te zijn en iets hoger naarmate de buitentemperatuur hoger is. De ventilatorspanning (die de uitblaasluchtsnelheid bepaalt) waarbij de maximale CSE wordt bereikt, is lager voor hogere buitentemperaturen. Dit is gerelateerd aan lagere drijvende krachten voor de luchtstroming van buiten naar binnen bij hogere buitentemperaturen. Deze resultaten zijn in overeenstemming met eerdere bevindingen en met resultaten die in de literatuur zijn gerapporteerd.

Perspectief toepassing

Drukverschil over deuropening.

Uit eerder onderzoek is gebleken dat van de onderzochte parameters, het temperatuurverschil over de deuropening de grootste invloed heeft op de zogeheten kritische snelheid (dit is de snelheid waarbij de luchtstraal van het luchtgordijn de grond net raakt) en daarmee op de klimaatscheidingseffectiviteit CSE. Om het luchtgordijn automatisch te kunnen regelen zijn hiertoe in de huidige luchtgordijnen temperatuursensoren aangebracht in en rondom het luchtgordijn.

Uit de in deze studie uitgevoerde metingen is gebleken dat het drukverschil over de deuropening eveneens een grote invloed heeft op de CSE. Om dit effect mee te kunnen nemen in de regeling, dienen ook drukverschil sensoren te worden aangebracht in en rondom het luchtgordijn (en de deuropening) om ervoor te zorgen dat op elk moment van de dag met de kritische snelheid wordt uitgeblazen. Op dit moment zijn er al potentiële drukverschilsensoren aangeschaft en testen zijn begonnen om na te gaan of deze in de praktijk (bij winkeldeuren) standaard geïnstalleerd kunnen worden.

Invloed van personen die door de deuropening lopen

De factor “aantal personen die door de deur lopen” is niet uitgebreid onderzocht. Meer experimenten zijn nodig om vast te kunnen stellen of, en zo ja onder welke omstandigheden, ook bij frequente passages van personen door het luchtgordijn, de herstelsnelheid van de luchtstroom voldoende groot is. Zo zou de regeling aangepast kunnen worden aan de frequentie van passages van personen door het luchtgordijn.

Bijdrage van het project aan de doelstellingen van de regeling

Aangezien op dit moment de luchtgordijnen alleen op basis van temperatuurschommelingen worden geregeld, kan het voorkomen dat een luchtgordijn niet in de optimale stand staat ingesteld. Er zijn echter meer factoren die invloed hebben op de kritische snelheid en daarmee op de klimaatscheidingseffectiviteit CSE. Factoren als wind, drukverschil, aantal personen die door de deur lopen, en uitblaastemperatuur hebben allen invloed op de kritische snelheid en de klimaatscheidingseffectiviteit. De invloed van deze factoren is onderzocht in dit onderzoek en zullen bijdragen aan energiebesparende maatregelen (d.m.v. een slimmer regelalgoritme) in winkels en bij toepassingen van industriële luchtgordijnen.

Naast direct praktisch toepasbare resultaten in de vorm van een verbeterd regelalgoritme heeft het project kennis opgeleverd in de vorm van een gevalideerd CFD model van een luchtgordijn waarmee systemen in andere toepassingen kunnen worden verbeterd, zoals luchtgordijnen van koelvitrines in supermarkten.

Tenslotte hebben de resultaten bijgedragen aan de ontwikkeling van de meetfaciliteiten bij TNO (zoals variabele openingen boven een luchtgordijn), die als een van de weinige in Europa in staat zijn om de efficiency van luchtgordijnen te meten.

Spin-off binnen en buiten de sector

Luchtgordijnen worden toegepast in verschillende soorten gebouwen (winkels, supermarkten, industriële gebouwen, overheidsgebouwen). Alhoewel de metingen uit dit onderzoek zich toespitste op comfort luchtgordijnen, kan de verkregen informatie ook helpen in het begrijpen van luchtstroming door de deur, waardoor niet alleen regelingen voor comfort luchtgordijnen, maar ook voor bijvoorbeeld industriële luchtgordijnen geoptimaliseerd of gecreëerd kunnen worden.

Naar beneden gerichte luchtstralen komen in meer toepassingen voor, bijvoorbeeld in de koelvitrines van supermarkten, of bij het droogblazen van componenten op een printplaat. Resultaten uit dit onderzoek, of het CFD-model zou gebruikt kunnen worden als input voor onderzoek naar luchtstroming in dergelijke toepassingen.

Management Summary

For easy access to shops or warehouses, an open doorway is sometimes used. If outside is colder than inside, this will result is significant heat losses through the door opening, which can be significantly reduced using an air curtain above the door opening.

Air curtain performance is expressed by a parameter called Climate Separation Efficiency (CSE) which is the degree to which an air curtain can reduce heat losses compared to the case of an open doorway (i.e. with the air curtain switched off). This project, jointly carried out by TNO and manufacturer of air curtains Biddle, was intended to improve the performance of such an air curtain where possible.

State-of-the-art in understanding of the factors that affect performance

A literature survey was carried out on air curtain factors that affect its performance. The crucial effect to achieve is for the jet of air coming from the air curtain to reach the floor beneath it. When the jet has too little velocity (in fact: momentum), it will fail to reach the floor with the effect that cold air will enter across the floor. When the air speed exceeds a certain optimal value, the indoor and outdoor climates will be less efficiently separated.

The effect can be described by a dimensionless number called the deflection modulus (D_m), which is the ratio of the momentum flux of the jet at the curtain outlet to the transverse forces due to air density difference across the doorway.

Apart from geometrical factors like the width and height of the doorway (which are mostly fixed in a particular application), the main parameters determining D_m are:

- temperatures of indoor air, outdoor air and outlet temperature,
- jet outlet velocity,
- jet outlet angle and
- outlet width

End-user needs and related Key Performance Indicators (KPI's),

In workshops with customers, air curtain manufacturer Biddle (partner in the project) noted that thermal comfort for cashiers sitting near the entrance was an important issue. Comfort is negatively affected by draughts coming from the door opening. Factors resulting in a decline in comfort from draughts include:

- temperature of the draughts,
- exfiltration caused by high-level openings above the doorway, typical of a building that is not fully airtight,
- human traffic through the doorway (i.e. people walking through the air curtain)

To limit the discomfort from draughts, the air jet from the air curtain is often heated to a maximum of 35°C.

Operational scope of parameters

From a review of the literature (Hendriksen, 2017), interviews with customers by Biddle and taking account of the results of previous studies, a number of operating conditions were selected to be investigated in this study. These operating conditions and their operational range are summarized in the table below.

Operating condition	Range	Remarks
temperature of indoor air	21°C	Common indoor temperature in shops
temperature of outdoor air	0-15°C	Common ambient temperatures in the Dutch heating season
outlet temperature	20-35°C	no heating: indoor temp, max: determined by comfort issues
jet outlet velocity	1-5m/s	typical of Biddle Comfort air curtains
jet outlet angle	0-10 degr	reported in the literature
outlet width	4-6cm	typical of Biddle Comfort air curtains
Neutral height related to high-level openings	60-80%	70% was typically measured by Biddle in a practical situation
People walking through the air curtain	1-60 per minute	Due to budget constraints, only a single experiment was carried out (no CFD)

Description of a base case including relevant geometries

The base case is represented by an air curtain set-up in the TNO MEC lab, consisting of a Biddle Comfort air curtain mounted above a door opening which is 2m wide and 2.3m high. This set-up is called the ‘full scale air curtain’.

In view of the importance of the effect of a high-level opening, the doorway in the TNO lab was reduced to a height of 1m (keeping a width of 2m) with additional openings above it. This is called the ‘reduced height air curtain’. The experimental set-ups are described in more detail in chapter 3.

In addition, a CFD model was made of both the ‘full scale’ and ‘reduced height’ air curtain in the TNO test rig. The CFD model is described in detail in chapter 4.

Focus of the project.

The effect of the parameters mentioned in the table above was assessed by determining the CSE (Climate Separation Efficiency) at a range of jet outlet velocities (or fan speeds). Experimental results were compared to CFD calculations.

Currently, Biddle is controlling parameters such as outlet velocity of their air curtains to achieve optimal performance (CSE). The aim of the current study is to gain insight into the effects of the parameters described above, paving the way to an improved control algorithm, optimising air curtain performance under a wider range of operating conditions.

Conclusions

The main conclusions that can be drawn from our results are the following.

- In our experiments and CFD simulations large amounts of data were generated, such as velocities and temperatures of air flows at a wide range of operating conditions. The most useful quantity to condense the results into and compare experiment and CFD simulations, appeared to be Climate Separation Efficiency CSE.

- When comparing CSE's, in general, reasonable to good agreement was found between experiments and CFD simulations. This shows that our CFD model is a very useful tool to predict the performance of an air curtain under a range of operating conditions.
- Unfortunately, running a single CFD scenario took much longer than anticipated (typically 2 days) due to the required detail of the model and dynamics of the flow processes taking place. Consequently, the number of CFD simulations were limited by the time and budget available.
- When varying cold room temperature ('outside'), keeping the warm room temperature ('indoor') constant, maximum CSE appeared to be in the range of 70%-80%. CSE is somewhat higher at higher outdoor temperatures. The fan voltage (determining outlet air speed) at which maximal CSE is achieved, is lower for higher outdoor temperatures. This can be related to lower air density differences and hence lower driving forces for the air flows from outside to inside. These results are consistent with earlier findings and results reported in the literature.

Contents

1 Introduction

In situations where a temperature difference exists between indoor and outdoor climates, an air curtain mounted above an open doorway can significantly reduce heat losses through the doorway.

Air curtain performance is expressed by a parameter called Climate Separation Efficiency (CSE) which is the degree to which an air curtain can reduce heat losses compared to the case of an open doorway (i.e. with the air curtain switched off).

To be effective the jet of air coming from the air curtain must reach the floor beneath it. When the jet has too little velocity (in fact: momentum), it will fail to reach the floor with the effect that cold air will enter the building across the floor. At a certain critical velocity, climate separation between indoor and outdoor will be achieved. Increasing the velocity will have the effect of the jet spreading across the floor, illustrated in Figure 1.

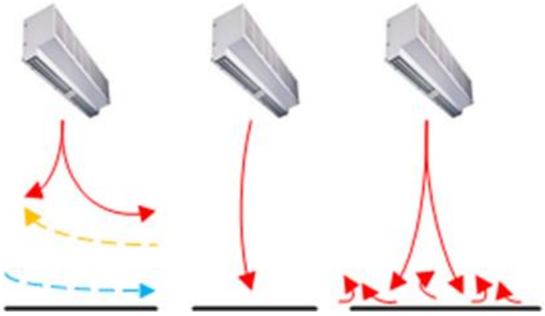

Figure 1: Climate separation efficiency depending on the velocity (momentum) of the air jet from the air curtain.

If anything, the indoor and outdoor climates will be less efficiently separated when the air speed exceeds the optimal value. This will be a recurring phenomenon in our study.

Air curtain manufacturer Biddle is controlling parameters such as outlet velocity of their air curtains to achieve optimal performance (CSE). The aim of the current study is to gain insight into effects such as temperature difference between indoor and outdoor climates, heat input to the air jet, disturbance of the air jet from people walking through it, presence of openings above the curtain (e.g. due to air leakages in the building) and air jet outlet angle. The insights pave the way to an improved control algorithm, optimising air curtain performance under a wider range of operating conditions.

In this study, a Biddle Comfort air curtain was tested experimentally at the MEC lab of TNO. In addition, a CFD model was made of the air curtain in the TNO test rig. Experimental results are compared to CFD calculations under a range of operating conditions. Analysis of the results has led to suggestions for an improved control algorithm.

2 Theory

2.1 Climate Separation Efficiency of an air curtain

An air curtain is assumed to be placed over an opening between a cold room ('outdoor') and a warm room ('indoor'). Initially, the opening underneath the air curtain is closed. Then, at t=0 it is opened, and due to buoyancy forces, cold air from the cold room will enter the warm room at low level while displacing warm air as flow reversal through the door at high-level.

The jet from the air curtain serves as a barrier to prevent these flows, keeping the warm air inside and the cold air outside, thus achieving a 'climate separation'. The efficiency of the air curtain in achieving this is expressed as the 'Climate Separation Efficiency' (CSE). It is defined as the ratio of heat losses with the air curtain operating and heat loss without an air curtain:

$$CSE = 1 - P_{\text{air curtain}} / P_{\text{no air curtain}} \qquad [1]$$

with P denoting heat loss power [W]. Obviously, the better the CSE, the lower the exchange of heat between both rooms.

The Climate Separation Efficiency is determined both experimentally (chapter 3) and numerically using a CFD model (chapter 4) In both cases, eq. [1] is used to determine CSE.

2.2 Deflection modulus

From the literature, it appears that an important parameter determining CSE is the deflection modulus D_m. It is a dimensionless number giving the ratio of the momentum flux of the jet at the curtain outlet to the transverse forces due to the density difference across the doorway (D. Frank, P.F. Linden, Fluid Mech. (2014),

$$D_m = \frac{\rho_0 b_0 u_0^2}{g h_b^2 (\rho_d - \rho_l)} = \frac{b_0 u_0^2}{g h_b^2 \left(\frac{T_0}{T_d} - \frac{T_0}{T_l} \right)} \qquad [2]$$

With:

ρ_0 = density air jet

ρ_d = density air outside (dense)

ρ_l = density air inside (light)

b_0 = width outlet

u_0 = jet outlet velocity

g = gravity constant (9.81 m/s^2)

h_b = height doorway

T_0 = initial temperature outlet

T_d = temperature air outside (dense)

T_l = temperature air inside (light).

For situations where the outlet temperature T_0 equals the indoor temperature T_I, the equation simplifies to:

$$D_m = b_0 u_0^2/gh_b^2 (T_I-T_d)/T_d \qquad [3]$$

This shows that in order to correctly calculate the deflection modulus, it is crucial to obtain a reliable measure of the temperature difference between the two rooms T_I-T_d, in particular when it is a small number.

2.3 Theoretical heat losses with no air curtain operating

In order to determine the CSE from eq. [1], we need to know the heat losses without an air curtain. In our experimental setup, these are generally too large to allow an accurate measurement. Therefore, heat losses without an air curtain operating are approximated by a theoretical value, shown below.

$$Q = \rho_1 . c_p . b . h . \frac{1}{5} . U_c . \Delta T$$
$$U_c = \sqrt{g . h . \Delta T / T_2} \qquad [4]$$

With:

Q = heat loss through door opening [kW]

ρ_1 = density of air in cold cell = 1.257 kg/m³

c_p = specific heat of air = 1.006 kJ/kg·K

b = door width = 2m

h = door height = 2.3m

Uc = convection velocity [m/s]

ΔT = temperature difference between cold and warm cells [K]

g = gravitational acceleration = 9.81 m/s²

T2 = temperature in warm cell [K]

If temperatures of warm and cold cells are 21 °C and 6.7 °C respectively, the convection velocity is 1.047 m/s and the heat loss Q = 17.4 kW (= 3.8 kW/m²)

2.4 Theoretical heat losses with no air curtain and high-level opening

With a sealed room, the warm air inflow equals the cooler outflow through the door opening. At the vertical midpoint, the pressure inside and outside the room is the same and there is no net flow of air. This is defined as the neutral height (h_N). However, a room high-level opening provides an additional air flow path and the result is to raise the neutral height. There is thus, in the case of a heated room, a greater proportion of the door from the ground where outside air enters the heated room. This is matched by the sum of the outward flow from the reduced door opening above the neutral height, and the high-level opening flow itself. For the case where the neutral height is sufficiently high, there is only air inflow through the door.

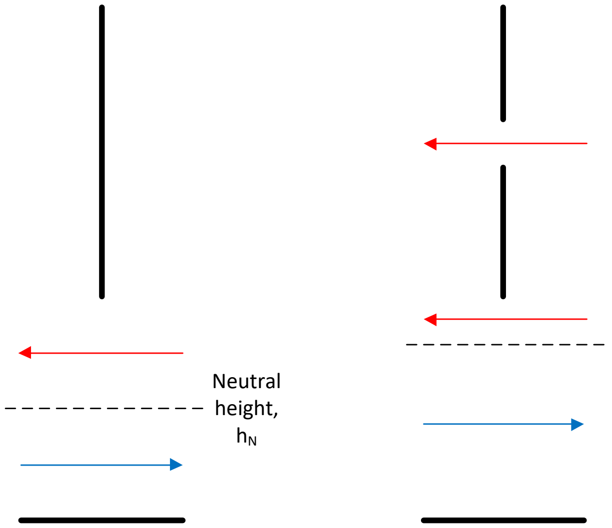

Figure 2: Flow variation with change in neutral height. Mid-level neutral height with a sealed room (left) and raised with a high-level opening.

The equations to calculate neutral height and flows through the door and a high-level opening are given by [1] (Frank) as a function of door and opening dimensions. These dimensional references, assuming square / rectangular openings, are given in Figure 3.

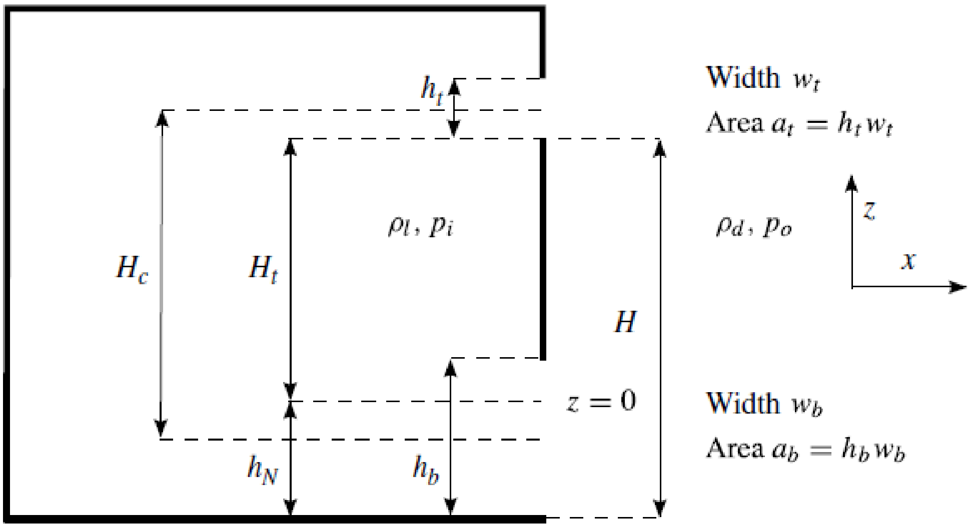

Figure 3 Notations used in the calculation of the neutral height and airflows

The neutral height is given as a function of door area, high-level opening area, the height to the top of the door and the height to the bottom of the high-level opening:

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[1] D. Frank en P.F. Linden, Fluid Mech. (2014), vol.756, pp. 130-164

$$\frac{a_t}{a_b} = \frac{2}{3}\left(\left(\frac{h_N}{h_b}\right)^{3/2} - \left(1 - \frac{h_N}{h_b}\right)^{3/2}\right)\sqrt{\frac{h_b}{H - h_N}}.$$

From this, depending on the air densities in the two spaces, the flow below the neutral height through the door can be calculated, along with the opposing outflows through the remainder of the door and the opening:

$$q_{in} = w_b C_b \int_{-h_N}^{0} \sqrt{2g'}\sqrt{(-z)}\,\mathrm{d}z = \tfrac{2}{3} w_b C_b \sqrt{2g'} h_N^{3/2}$$

$$q_{out,b} = w_b C_b \int_{0}^{h_b - h_N} \sqrt{2g' z}\,\mathrm{d}z = \tfrac{2}{3} w_b C_b \sqrt{2g'}(h_b - h_N)^{3/2};$$

$$q_{out,t} \approx C_t a_t \sqrt{2g' H_t}.$$

The discharge coefficients *C* for the bottom and top openings are assumed the same at ~0.6, equivalent to a sharp-edged opening.

g' is the density difference ratio, defined as $g' = g\left(1 - \frac{\rho_w}{\rho_c}\right)$

with g the gravitational acceleration (9.81m/s^2) and ρ the density of the warm or cold air depending on the subscript.

The sensible heat transfer can then be calculated based on the air mass flow rate (volume flow rate and density product), specific heat capacity and temperature difference between the two spaces:

$Q = \dot{V}\rho C_p(T_w - T_c)$

Note that the equations above are based on conservation of volume, but since the densities are slightly different there is not conservation of mass and the resulting heat transfer is slightly different depending on the use of the warm or cold air density. Therefore, in subsequent reference cases, for heat loss calculations based on air volume transfer the cold room air density is used, to maintain consistency with the calculations in section 2.3.

As previously described, the effectiveness of an air curtain is based on the heat loss through a door with a curtain compared to the door-only case. With a high-level opening, for the same door geometry and air temperatures there is a different air flow rate and hence heat loss. Therefore, for calculating the CSE with a high-level opening (eq. [1]) the "$P_{\text{no air curtain}}$" is calculated for the with-opening case as described above rather than in section 2.3.

3 Experimental set-up

3.1 Full scale air curtain (2.3m high)

The air curtain is mounted between two rooms of about **4**x**4**x**6**m (**w**x**h**x**d**). One of these is the ‘warm’ room, generally held at a temperature of 21°C by a heating unit, while the other is the ‘cold’ room, held at temperatures between 3 and 10 °C by a cooling unit. The opening between the rooms, with the air curtain above it, can be closed by two hinged doors, shown in Figure 4.

Figure 4: The cold room with a view of the wall separating it from the warm room. The 9 vertical wires are connected to temperature sensors (mounted at three different heights)

3.2 Reduced height air curtain (1m high)

A number of experiments were carried out with the air curtain mounted at a lower height. This allows for panels above the air curtain to be opened, simulating a building that is not fully airtight. Figure 5 shows the air curtain at a height of 1m, with the two hinged doors underneath it opened. The panels within panels above the air curtain are shown in more detail in Figure 6.

Figure 5: Installation of the air curtain at 1m height, view from the warm room.

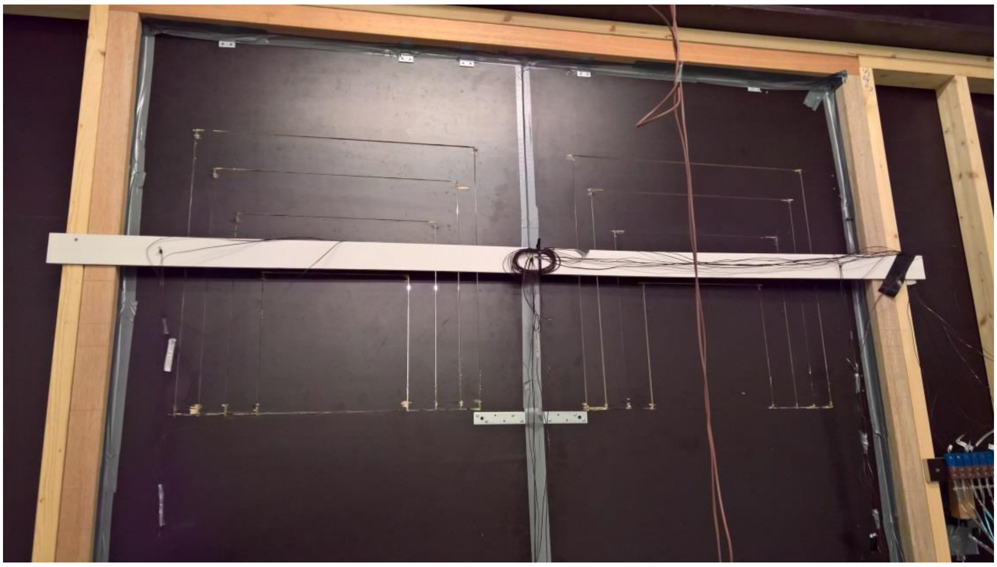

Figure 6: Panels within panels above the air curtain to achieve different sized high-level openings

3.3 Determination of Climate Separation Efficiency

The measurement method for the high and the low air curtain is identical. With the hinged doors closed and the air curtain operating, the rooms are left for some time to reach a steady state. Then, the doors are slowly opened [2] and density differences result in cool air passing through the door at low level, displacing the warm air into the cold room. The better the CSE from the air curtain, the lower the exchange of air between both rooms.

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[2] To minimise mixing of air when opening the doors, sliding doors would be better than hinged doors.

The heating unit within the warm room’s air recirculation system attempts to maintain the warm room at its initial temperature, countering the heat losses to the cold room. Similarly, the cooling unit will attempt to maintain the cold room at its initial temperature, countering the heat gains from the warm room. As maintaining the initial temperatures is generally not possible, the temperature of the air is measured at 27 locations across each room.

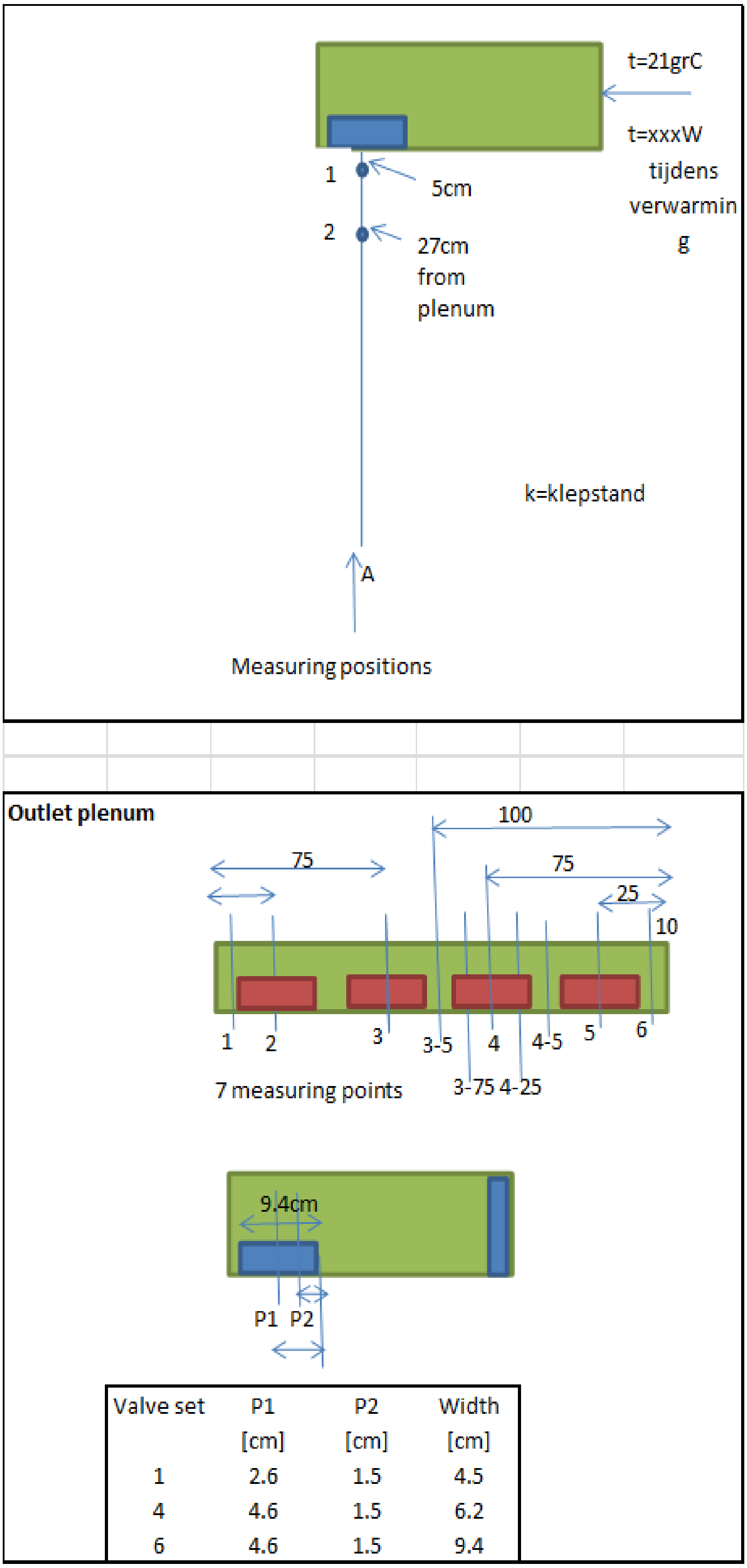
After a period of 8 minutes, the hinged doors are shut and the heating unit and cooling units will return the rooms to their initial conditions (generally within 1-2 hours). In the end, the heat losses in the 8-minute experiment are calculated from the amount of heat supplied by the heater from the moment the hinged doors are opened until the initial conditions are once again reached. This should be identical to the amount of heat dissipated by the chiller in that period. A correction is made for heat losses and heat gains from the test rooms to/from the environment using data obtained from prior calibration tests.

A report was made on the detailed experimental results (Hamming, 2017).

3.4 Measurement of air velocity and temperature profiles

Note that velocities are referred to throughout this report, which strictly speaking are speeds with no directional component. However, in the region within the jet the direction of flow can reasonably be assumed as downwards. Measurements were made of air speed profiles and temperature profiles at different positions and heights underneath the curtain. The purpose was to compare these to profiles derived from the CFD simulations in order to validate the latter (see chapter 4.4).

The chamber airflow volumes could not be measured directly as they were very large and there is no dedicated measuring section in the air handling units or ducting. An estimate of chamber flow was made by an airspeed traverse over a 16-point grid in front of the diffuser wall in each chamber. This was repeated for several fan speeds of the chamber air handling unit. These flows were input to the CFD model.



Valve set	P1 [cm]	P2 [cm]	Width [cm]
1	2.6	1.5	4.5
4	4.6	1.5	6.2
6	4.6	1.5	9.4

Figure 7: location of sensors in measuring velocity and temperature profiles

4 CFD model

4.1 Description

The 3D mesh for the CFD computations was made using GRIDGEN version 15. A CAD file was provided by Biddle and used to generate the mesh. A hexahedral mesh was built which was refined by a factor of two in each direction near the air curtain to achieve a higher accuracy in this region. The final model consisted of approximate 660,000 cells. Because the air speeds were assumed to be symmetrical from the middle, only half of the test chamber and air curtain is modelled to reduce computational time.

A plot of the geometry is shown in Figure 8 with the location of the chamber air inlets and outlets on the left and the location of the air curtain inlet and outlet on the right. An impression of the mesh is shown in Figure 9.

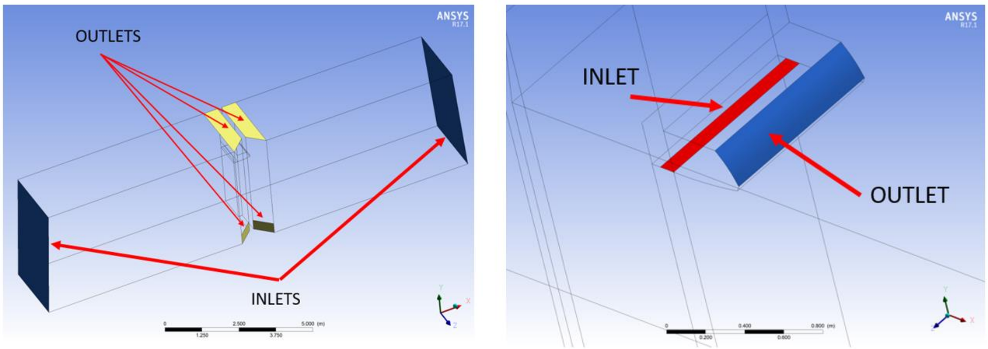


Figure 8 CFD model geometry of the chamber air inlets and outlets (left) and a detailed view of the air curtain inlet and outlet (right).

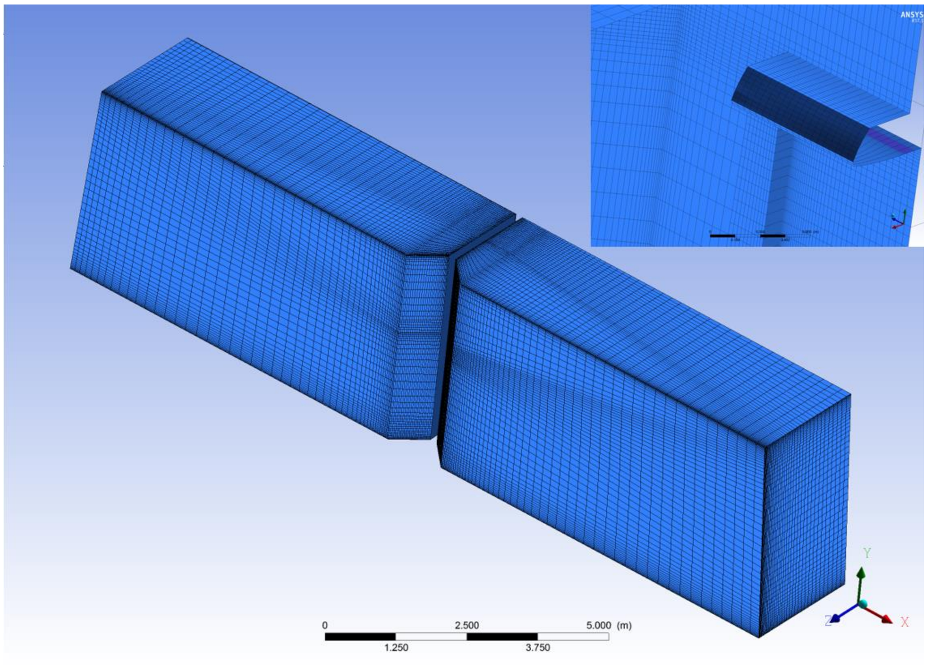


Figure 9 Impression of the mesh of the CFD model with a detailed view of the air curtain in the top right corner.

The CFD model was set up and run in ANSYS Fluent version 16.1. For the turbulence model, the k-w SST with Low-Re Corrections was applied.

The fluid flow is assumed to be incompressible and the air has a constant density. As the temperature differences are small, the Boussinesq approximation was used to model the influence of density differences due to temperature [Belleghem *et al.*]. Table 1 shows the materials properties of air that were used.

Table 1 Material properties of the air used in the CFD model

Property of air	**value**	**unit**
Density	1.184	kg/m^3
Viscosity	1.789e-05	Pa·s
Specific heat	1006	J/(kg·K)
Thermal conductivity	0.0242	W/(m·K)
Thermal expansion coefficient	0.00343	K^{-1}

All the inlets were modelled by specifying the velocities at the boundaries. At the outlets, the percentage of the total mass flow leaving the domain is specified.

The temperature of the air curtain is calculated from the average temperature of the inlet of the air curtain device incremented by the heating power. All the walls have a no slip flow boundary condition and a zero heat-flux boundary condition. The reason for the latter approximation is that floors and walls are thermally insulated and therefore heat transfer to floor and walls is negligible on the time scale of the simulations (2 min, see below).

4.2 Duration of simulation

The CFD simulations cover the first 120s after the opening of the doors at t=0. An 8-minute duration, as was used in the experiments (chapter 3), was not done as it takes approx. 2½ days to run a 120s CFD scenario. Calculation of 8 minutes would be impractically long.

The assumption was that while the initial part of the process is more transient, 120s is sufficient simulation time such that CSE does not depend on the duration of the experiment/simulation. This was verified in a single CFD simulation, lasting for 8 minutes (480s), see Figure 10.

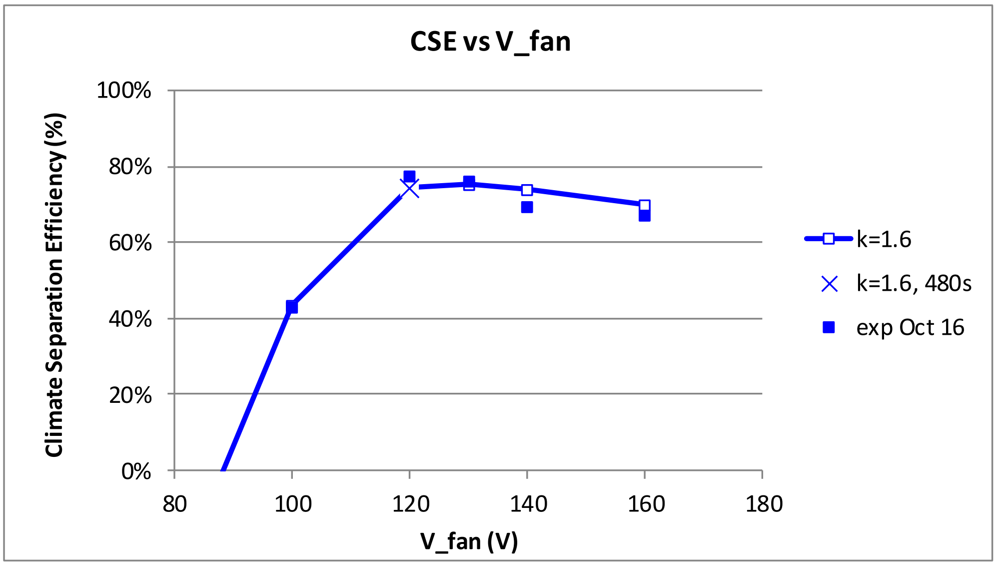


Figure 10 CSE vs fan voltage. CFD simulations of 120s compared to experiments of 480s and a single CFD simulation of 480s.

4.3 Determination of Climate Separation Efficiency

The determination of the heat losses and therefore, CSE is slightly different from those in the experiments. In the experiments, there are quite large temperature differences in the various regions of each room at the time the doors are shut, hence with a limited number of temperature sensors the rooms need to return to their stable, original conditions for evaluating heat balances.

At the end of the simulation at 120 s, the temperature of each cell in the rooms is known and these are used to calculate the heat added or removed, required to bring each room to its initial temperature.

4.4 Velocity profile

The velocity profile measured experimentally at a distance of 2 cm underneath the curtain serves as the initial profile for the CFD calculations. However, the velocity profile, when integrated over the outlet area, produced a volume flow rate which differed by a factor of two from flow rates directly measured by Biddle for this curtain. This is unsurprising as the width of the outlet is small and large speed variations occur over small distances. As direct measurements of flow rates are more reliable and accurate than integrating velocity profiles, we decided to scale the velocity profiles to fit the flow rates measured.

We had the choice of scaling every point in the profile by the same factor or by scaling the higher velocities more than the lower ones by using a power of 1.6. The latter produces the same maximal velocities as the initial ones but reduces lower velocities more than the first scaling does. The scaling process is illustrated in Figure 11.

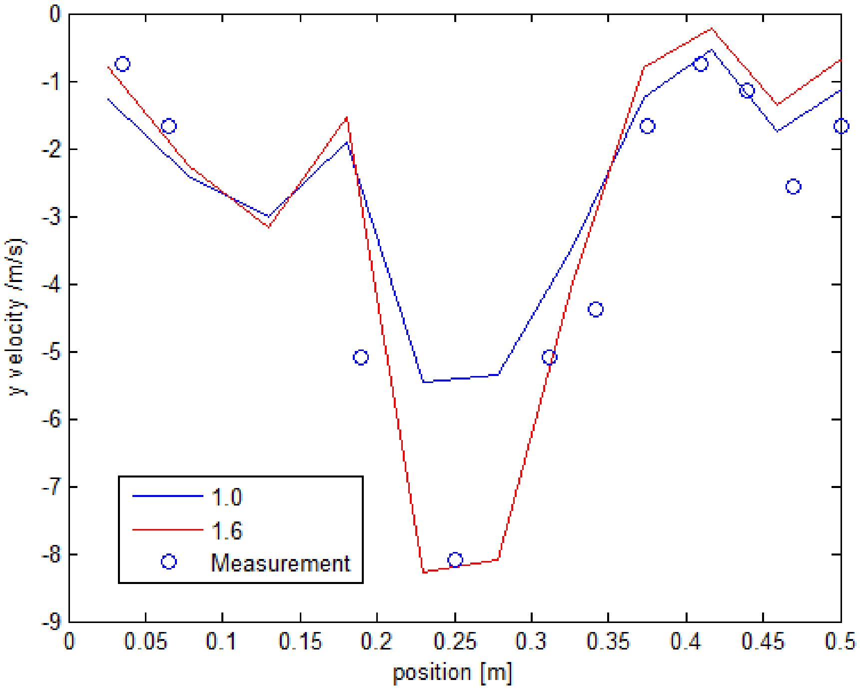


Figure 11 Example scaling of outlet velocities to match experimentally determined volume flow rates along a length covering 1 fan (0.5m). The profile also varies in the width axis.

Using both profiles for initial outlet velocities in our CFD simulations, we compared velocities calculated further below the curtain to experimentally measured velocities. Unfortunately, the comparison did not provide conclusive evidence for the best choice of scaling. The left of Figure 12 illustrates that the k=1.0 scaling (green line) produces more agreement near the floor, while the k=1.6 scaling (red line) produced a better agreement near the outlet of the air curtain.

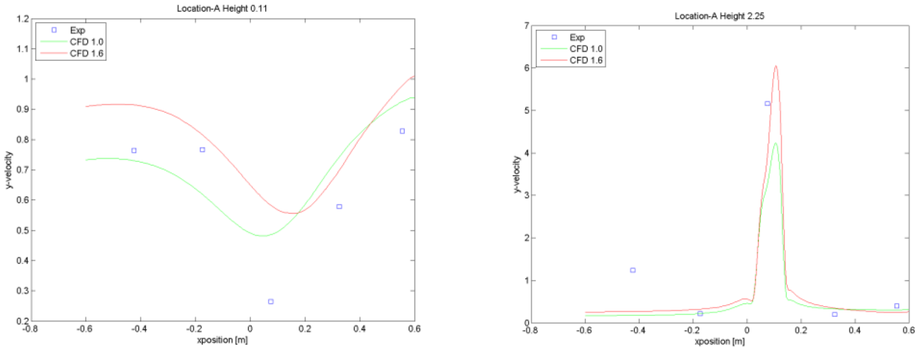


Figure 12 Velocities at a height of 0.11m above the ground (left) and 2.25m (5 cm below the curtain). The blue symbols denote experimental values, the lines denote the CFD simulations (red line k=1.6, green line, k=1.0).

Since it is uncertain at which height above the floor a good match between experiment and CFD simulation is most crucial, we decided to use the best match with experimentally determined CSE as the criterion for the selection of the scaling procedure. Figure 13 and Figure 14 show the experimentally determined CSEs (blue symbols), both from our latest experiments in October 2016 and from previous experiments in March 2016. They are compared to the CSEs calculated with the k=1.0 and the k=1.6 profile (red and blue line respectively). While Figure 13 shows CSE versus fan voltage (and therefore jet air speed), Figure 14 shows CSE versus the deflection modulus D_m.

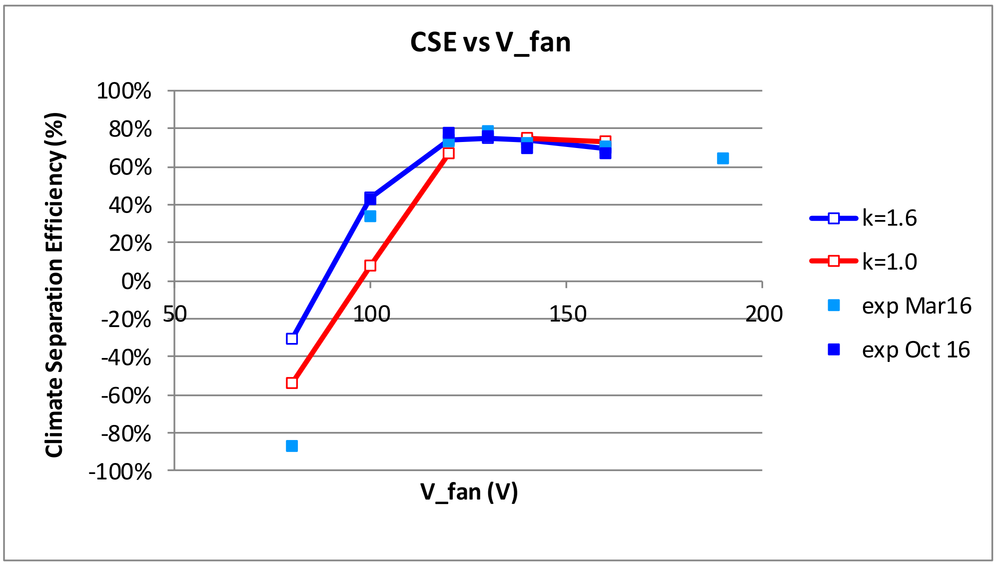


Figure 13 CSE vs. fan Voltage for the k=1.0 and k=1.6 velocity profile.

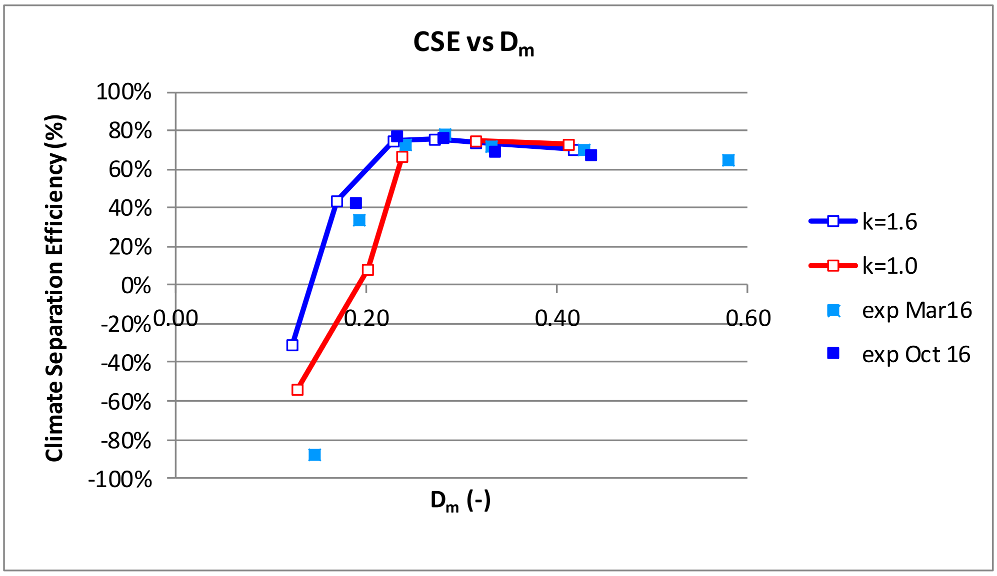


Figure 14 CSE vs. dimensionless number D_m for the k=1.0 and k=1.6 velocity profile.

Figure 13 and Figure 14 show that the k=1.6 profile gives a better match between experimental and calculated CSEs, so we used this scaling procedure in the remainder of our study.

5 Variation of operating conditions

From a review of the literature (Hendriksen, 2017) and user interviews with customers by Biddle, a number of operating conditions were selected to be investigated in this study. These operating conditions and their operational range are summarized in Table 2 below.

Table 2: Operating conditions to be investigated in this study and their operational range.

Operating condition	**Range**	**Remarks**
temperature of indoor air	21°C	Common indoor temperature in shops
temperature of outdoor air	0-15°C	Common ambient temperatures in the Dutch heating season
outlet temperature	20-35°C	no heating: indoor temp, max: determined by comfort issues
jet outlet velocity	1-5m/s	typical of Biddle Comfort air curtains
jet outlet angle	0-10 degr	reported in the literature
outlet width	4-6cm	typical of Biddle Comfort air curtains
Neutral height related to high-level openings	60-80%	70% was typically measured by Biddle in a practical situation
People walking through the air curtain	1-60 per minute	Due to budget constraints, only a single experiment was carried out (no CFD)

In each of these experiments, the results of the CFD simulations are compared to the results of the experiments, except the scenario with people walking through the air curtain, where only an experiment was carried out.

In the following chapters, the results are displayed as graphs of the Climate Separation Efficiency (CSE) vs. the fan voltages as well as vs. the deflection modulus D_m. The first are shown because fan voltage is a main control parameter for Biddle to achieve maximal CSE.

The relation between fan voltage and (mean) jet velocity for an outlet width of 6.5cm (valve setting 6) is shown in Figure 15 below.

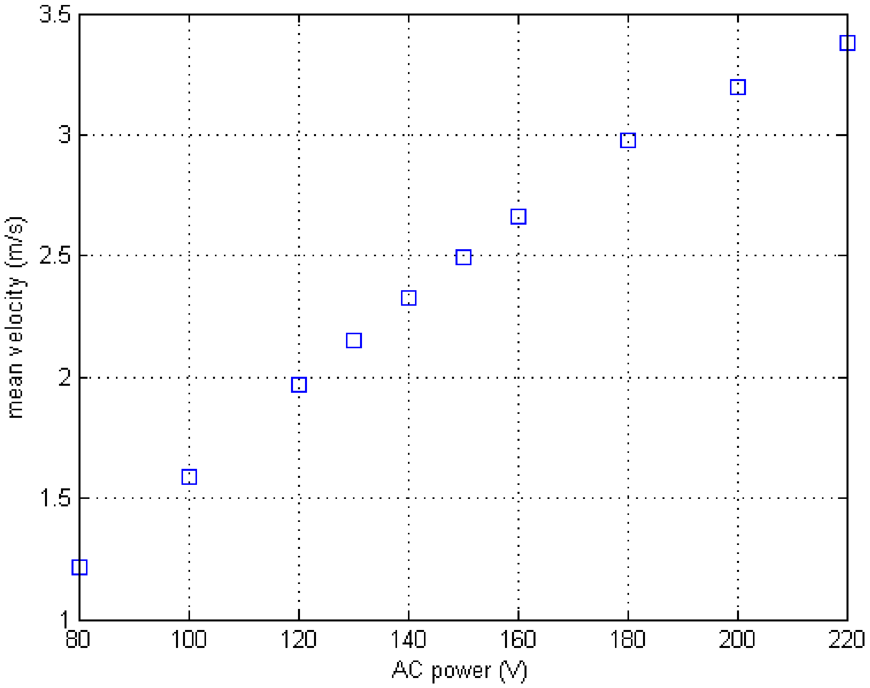


Figure 15: relation between fan voltage and (mean) jet velocity for an outlet width of 6.5cm (valve setting 6)

5.1 Variation of cold room temperature

An important parameter is the temperature difference across the door (i.e. between indoor and outdoor climates), as this determines the driving force for outdoor air entering through the doorway (and warm air escaping to the outside).

In this experiment and corresponding CFD calculations, we fixed the indoor temperature at 21°C and set outdoor temperature to: 3°C, 6.7°C and 11°C as these are conditions generally encountered in the Dutch winter climate. Outdoor temperatures below 3°C were not tested due to condensation and freezing problems anticipated with the cooling coil in the cold room air handling unit in the experimental set-up. For each outdoor temperature, we varied the voltage controlling the fan and therefore the outlet velocity of the air jet. The width of the outlet opening was fixed at 6.5 cm (valve setting 6), apart from a single curve at outdoor temperature of 3°C determined with an outlet opening of 4.2 cm (valve setting 1). The results are shown in Figure 16 and Figure 17.

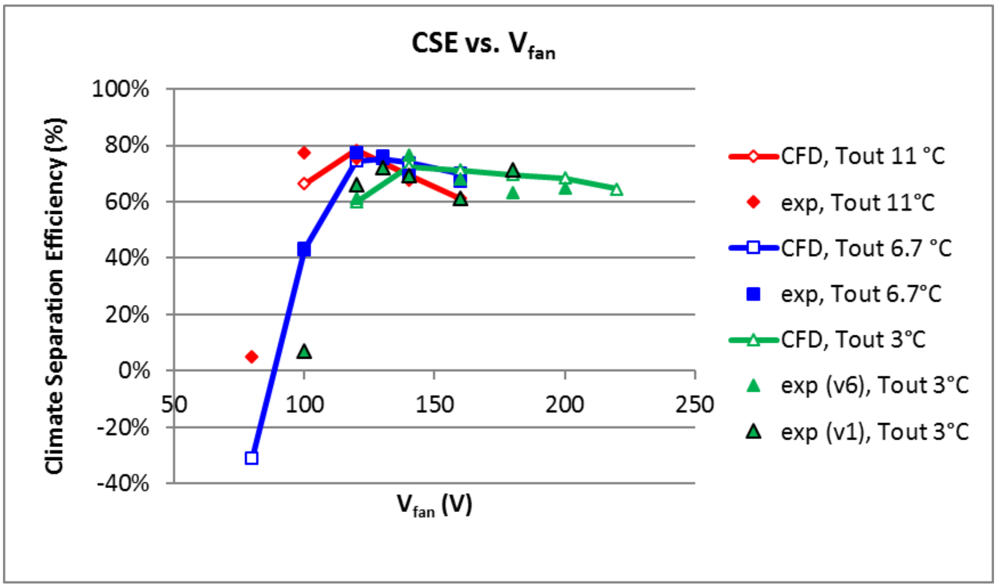


Figure 16 CSE vs. fan voltage for different cold room temperatures with indoor temperature fixed at 21°C. CFD simulations (lines) compared to experimental values (symbols).

Figure 16 seems to suggest that the optimal fan voltage is lower for smaller temperature differences between indoor and outdoor (i.e. at higher outdoor temperature when keeping the indoor temperature at 21°C). This is due to the buoyancy and therefore driving forces being lower at higher outdoor temperatures.

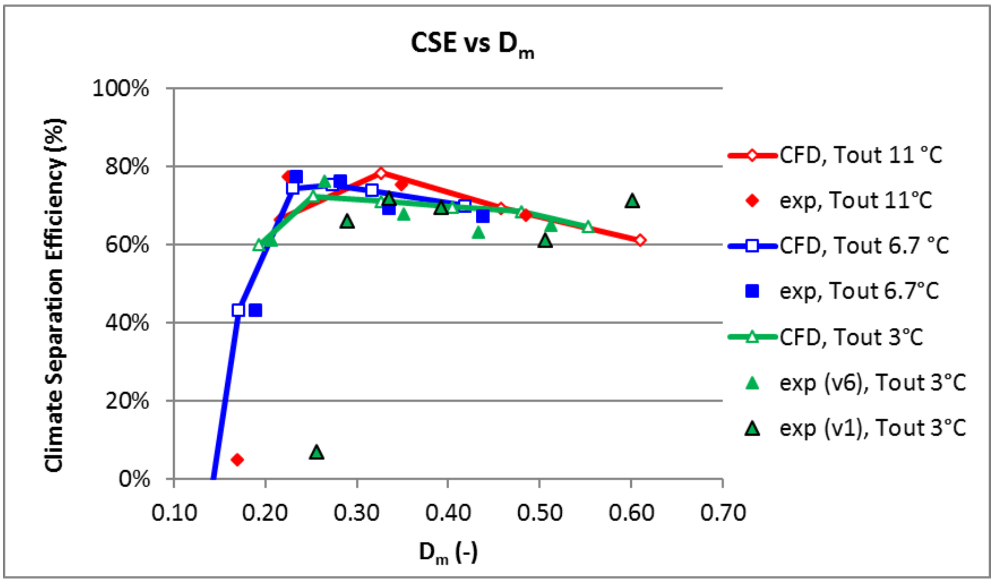


Figure 17 CSE vs. dimensionless number D_m for different cold room temperatures. Indoor temperature fixed at 21°C. CFD simulations (lines) compared to experimental values (symbols).

Figure 17 shows a good agreement between the CFD simulations (lines) and experimental values (symbols). Maximum CSE is between 70% and 80% and appears to be slightly higher for higher cold room temperatures. Maximal CSE is achieved at values of D_m between 0.25 and 0.3. Below 0.2, the air jet does not have enough momentum to reach the floor underneath the air curtain. In this region, with the CSE dropping off, the match is not so good but here the CSE sensitivity to fan voltage is significant. In any case, the curtain should not be operated too close to this point in practice.

At of D_m values higher than the optimal, CSE slightly decreases. However, CSE is still high enough to allow – in practical applications - a selection of a fan voltage somewhat higher than the optimal value to keep away from the region of rapidly dropping performance.

Some additional experiments were carried out at valve setting 1 which entails a smaller width of the curtain (4.2 cm instead of 6.5 cm). As Figure 16 and Figure 17 show, there is slight difference in CSE between both valve settings.

In these and subsequent plots, the blue symbols and blue lines denote our base case: T_{indoor} 21°C, $T_{outdoor}$ 6.7°C, with no heat input to the air curtain. For the experimental values, the results from the experiments carried out in October 2016 were used.

5.2 Effect of walking through the air curtain

Due to budget constraints, the effect of people walking through the air curtain was not assessed with CFD calculations but assessed only experimentally. A person walked through the curtain from the back of the warm room to the back of the other, paused for about 10 seconds, returned and repeated after a further pause. This was repeated for the test duration which resulted in two crossings (one each way) per minute. The results are shown in Figure 18 and Figure 19.

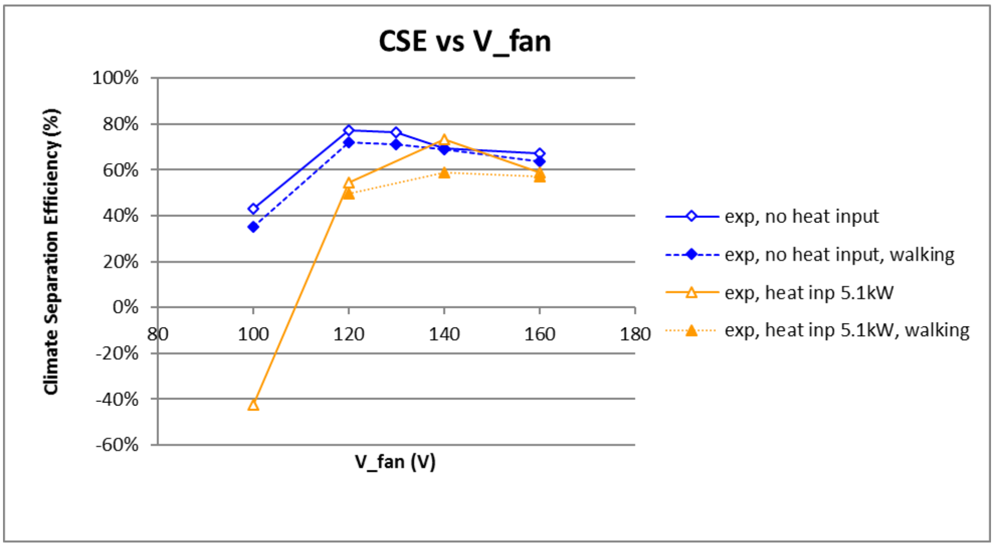


Figure 18 CSE vs. fan voltage (Voltage) for a person walking through the curtain and undisturbed, for unheated and heated discharge air.

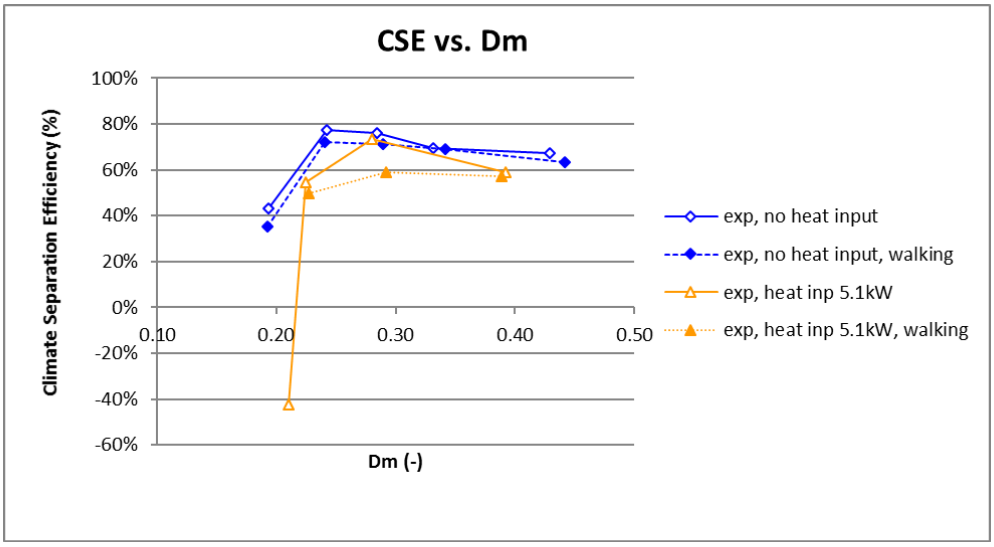


Figure 19 CSE vs. D_m for a person walking through the curtain and undisturbed, for unheated and heated discharge air.

Figure 18 and Figure 19 show that both for the unheated and heated discharge air, there is some but no dramatic decrease in CSE with someone walking through the air curtain under the conditions (approx. two single crossings per minute). The main purpose is to identify any evidence that suggests the fan speed should be set differently to take these passages into account. The CSE-maximising speed and D_m did not change much, including the scenario where the curtain jet was heated. Pedestrians will disturb the jet and a hypothesis was that a higher fan speed would re-establish the barrier more rapidly with a performance improvement. Apparently, the jet re-establishes itself rather quickly after its disturbance by a person crossing the doorway. From limited data, the flow seems rather robust to the disturbances applied. In order to better quantify the effect of pedestrians, a more thorough series of experiments would be needed to vary the frequency of traversing to see if heavy traffic would make a difference to optimum fan speeds.

6 Conclusions

The main conclusions that can be drawn from our results are the following.

- In our experiments and CFD simulations large amounts of data were generated, such as velocities and temperatures of air flows at a wide range of operating conditions. The most useful quantity to condense the results into and compare experiment and CFD simulations, appeared to be Climate Separation Efficiency CSE.
- When comparing CSE's, in general, reasonable to good agreement was found between experiments and CFD simulations. This shows that our CFD model is a very useful tool to predict the performance of an air curtain under a range of operating conditions.
- Unfortunately, running a single CFD scenario took much longer than anticipated (typically 2 days) due to the required detail of the model and dynamics of the flow processes taking place. Consequently, the number of CFD simulations were limited by the time and budget available.
- When varying cold room temperature ('outside'), keeping the warm room temperature ('indoor') constant, maximum CSE appeared to be in the range of 70%-80%. CSE is somewhat higher at higher outdoor temperatures. The fan voltage (determining outlet air speed) at which maximal CSE is achieved, is lower for higher outdoor temperatures. This can be related to lower air density differences and hence lower driving forces for the air flows from outside to inside. These results are consistent with earlier findings and results reported in the literature.

7 References

Hendriksen, L, literatuur studie luchtgordijn, internal TNO report, June 2017

Hammink, H, Resultaten Experimenten Biddle luchtgordijn, internal TNO report, June 2017

Belleghem, M.V, Verhaeghe, G, T‘Joen, C, Huisseune, H, De Jaeger, P, De Paepe, M, Heat transfer through vertically downward-blowing single-jet air curtains for cold rooms, Heat Transfer Engineering, 33 (14) (2012), pp. 1196-1206

8 Signature

Delft, October 2017	TNO
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9 Appendix A: Interview end-users

Reviewing the contacts between the Biddle sales department and customers, it appears that ever more question arise whether an air curtain can ‘block’ ventilation air (or infiltration air). Owners of large shops or warehouses are particularly interested in subjects like this, especially if the cashier area is located close to the opening. The cold draught from infiltration is likely to be experienced as uncomfortable, especially when an air curtain is not sufficiently heating the air jet.

Several workshops were held at Biddle to discuss these problems, as well as other common problems facing customers (in terms of climate separation / climate control). Visiting shops and warehouses are done on a weekly basis and many cashier employees were interviewed in due course.

Noise from the air curtain was not identified as an important issue related to the comfort of employees.