Modelling Airflow Rate through Perforated Benches in Greenhouses.

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Abstract

The purpose of the perforated bench is to reduce the air humidity beneath the plant canopy without excessive energy consumption. A bench heating system with heating pipes under a perforated bench with skirts creates an airflow through the bench openings due to buoyancy forces. Because the heated air is relatively dry compared to the surrounding air, it has a moisture absorbing and transporting capacity. The moisture transporting capacity will be decrease, thereby reducing the advantages of the perforated bench, if airflow rate is impeded by the bench structure, plant shape or leaf area index. Thus the airflow rate is of importance for the performance of a perforated bench.

In an experimental setup the airflow rate was determined for different perforated bench designs with and without plants. Measurements were carried out with five different plant types on four bench designs. It was found that the airflow rate was effected by the design of the perforated bench, but on the same type of bench the effect of plant type and leaf area index was insignificant.

A model to predict the airflow rate for each bench design as a function of temperature difference created by the bench heating system for the investigated bench designs is presented.

Keywords: Greenhouse, Heating, Thermal buoyancy, Ventilation, Perforated bench, Bench design, Plant effect.

Introduction

The perforated bench technology has been used for a decade, but so far no reports on air flow rates, using buoyancy driven flow, have been reported.

The purpose of conventional ventilation in greenhouses is to homogenise the air temperature in the greenhouse and to reduce air humidity in the plant canopy zone (between the bench surface and the plant upper canopy). Traditionally centrally measured air temperature and air humidity determines the extent of ventilation- and heating-efforts in a greenhouse environment. The measured climate in the middle of the greenhouse is assumed representative for the local climate in the plant zone when adjusted according to empirical knowledge. For example if the centrally measured air humidity is less than 85%RH the relative humidity in the plant zone is assumed less than 100% RH. For control purposes it would be preferable to measure and be able to regulate the climate in the plant zone independently of the climate in the surrounding greenhouse environment.

The perforated bench with skirts gives the growers the possibility to ventilate with air, heated with a sub-bench heating system. Heated air has the potential to transport humidity from the plant zone. It also heats the leaves thus counteracting the incidence of condensation on the plant canopy.

In order to increase the airflow rate through the perforated bench the bench is provided with tight fitted PP skirts around the perimeter, creating a confined air volume to direct the buoyancy driven airflow through the bench and the plant zone. The skirt is extending towards the floor leaving enough opening at floor level to allow sufficient air to enter the confined air volume. The vertical height of the bench skirt and the temperature difference between the air inside the bench confinement and the surrounding greenhouse temperature, determines the pressure difference over the bench and thus the air flow rate. The airflow rate can be regulated by increasing the heating power of the sub-bench heating system. If the air flow rate through the bench is dependent on variables such as bench design, plant shape or leaf area index (LAI) the performance of the bench ventilation system is not easily predictable .

Purpose

The purpose of the experiment were to investigate the effect on airflow rate for four bench designs and five plant types with different LAI. In order to show, the change in air flow rate dependency on leaf area index (LAI) on four types of perforated benches (one slatted bench and 3 trench benches), air flow measurements were performed, with different plant density and plant shapes.
On the basis of the measurements a model was sought to predict the airflow rate as a function of the temperature difference between air inside and outside the bench confinement.

Litterature review

In literature little effort has been called to investigate the effect on ventilation through perforated benches. Hausbeck M. K et al (1996) reported on the use of open-bottom benches to reduce the incidence of Botrytis stem blight and inoculum production. Many disputations concerning the ventilation in the whole greenhouse volume to decrease air moisture, has been submitted in literature. Among the most recent are Mistriotis A. et al (1997a, 1997b) and Boulard T. et al. (1999) who uses numerical methods to calculate the ventilation distribution in the greenhouse. Wang S. et al (1999), Baptista F.J. et al. (1999), Oca J. et al. (1999) and Boulard T. et al. (1997) used experimental methods to determine the ventilation in a greenhouse. Neither of the above has investigated the ventilation-rate in the plantzone or below the plant canopy.

Theory

The air through the perforations, form a free jet over the bench surface since the perforation itself, induces a pressure drop on the air and a increase in air velocity. Free jets are a flow structure that form when pushing a air volume through a contraction with a infinite volume on the low pressure side. After the outlet of the contraction the flow is divided into two flow regions types, the mixing volume at the periphery and the core volume in the centre. At the mixing volume a conventional mixing with the surrounding air takes place which slows down the air velocity. At the core volume the mixing has not developed and the flow velocity is uniform through the entire core volume. The extension of the core volume from the outlet point, depends on the design of the outlet area, and the air velocity through the contraction. Since the air velocity is constant through the entire core volume and the core area is almost equal to the perforation area at the outlet point, measuring the core velocity and the perforation area makes it able to calculate the air flow rate through the perforation.
According to theory the ventilation efficiency should be only limited influenced by increase in LAI or different plant shapes. At low air velocity the plants does not represent a contraction in the air flow direction, as does the bench itself, and there for should not induce a significant pressure drop compared to the pressure drop over the bench perforation. The maximum ventilation air flow rate $\dot{V}$ are limited by the differential pressure over the bench. If the differential pressure over the perforation openings exceeds the differential pressure of heated air under the bench confinement the air will begin to escape beneath the bench confinements at floor level, we call this counterflow.
The differential pressure of heated air under the bench Δp Nm^{-2} can be expressed by the equation

$$\Delta p = \rho g \beta H \Delta T_{in-out} \quad 1$$

where ρ is the air density, kgm^{-3}, g is the force of gravity, ms^{-2}, β is the volumetric thermal expansion coefficient, K^{-1}, H is the skirt vertical height, m, and $\Delta T_{in\text{-}out}$ is the temperature difference incoming-outgoing, K.

The bench opening have the same effect as a orifice in a flowing stream, the differential pressure are proportional to the square of the flow velocity. The differential pressure over the bench and the occurrence of counterflow is dependent on the bench design and specifically the perforation opening design. *This means that some corrections to the energy balance is necessary to predict the ventilation air flow rate. Though we use the energy balance to show some of the correlations between the parameters .*

The energy balance for this system, assuming that there are no heat loss from underneath the bench confinement, can be expressed by

$$q_{heat} = \rho \dot{V} c_p \Delta T_{in-out} + q_{loss} \quad 2$$

where q_{heat}[W] is the supplied heat, ρ is the air density [kgm^{-3}], c_p [$kJkg^{-1}K^{-1}$] is the heat capacity of air, $\dot{V}$ is the air flow rate [m^3s^{-1}] and $\Delta T_{\text{in-out}}$[K] is the temperature difference between inside and outside the bench confinement. q_{loss} is the conductive heat loss through the bench confinement (the side of the box and the bench surface area). The heat loss from the box and bench must be determined to complete the energy balance. The heat loss is measured when the box and perforated bench is closed for convection of out- and incoming air. The perforations are closed with air thigh insulation material that fits the individual perforation. The thermal conductivity coefficient, λ-value, can be calculated from measurements as

$$q_{loss} = \lambda A_{box} \Delta T \quad 3$$

where λ [$WK^{-1}m^{-2}$] is the conduction coefficient, q_{loss}[W] is the supplied power transformed into heat, A_{box} is the surface area of the box and bench and ΔT [K] is the temperature difference between inside and outside the bench confinement. The ΔT is not quite comparable to $\Delta T_{\text{in-out}}$ because the ventilation perforations have to be blocked to measure the heat loss under static conditions, but to calculate q_{loss} it is assumed that ΔT can be substituted by $\Delta T_{\text{in-out}}$.

The connection between ΔT and q_{loss} is linear and is calculated from measurements for the box with closed perforated bench and can be expressed by the equation:

$$q_{loss} = 13.6 \Delta T \quad 4$$

Materials and methods
Experimental Bench
The bench design and experimental set up is shown in fig. 1 and fig. 2.

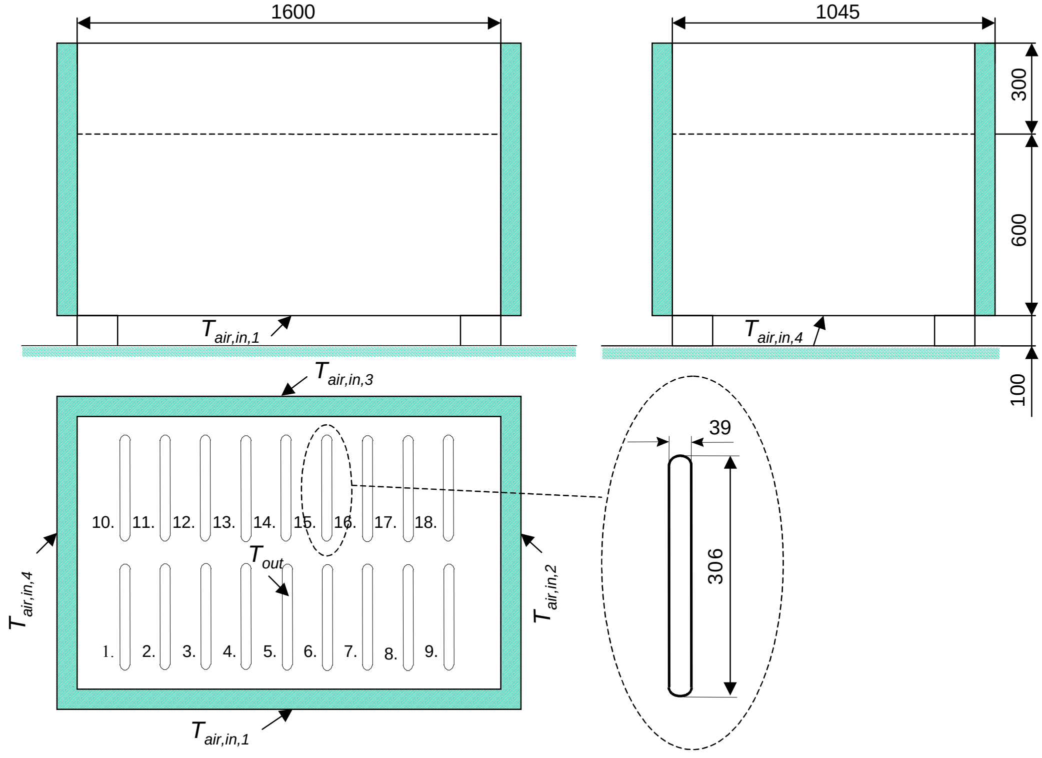

Fig. 1: Experimental set up of perforated bench, BNR=1, and insulated box. Dimensions in mm. Measurement position are shown at the arrow point.

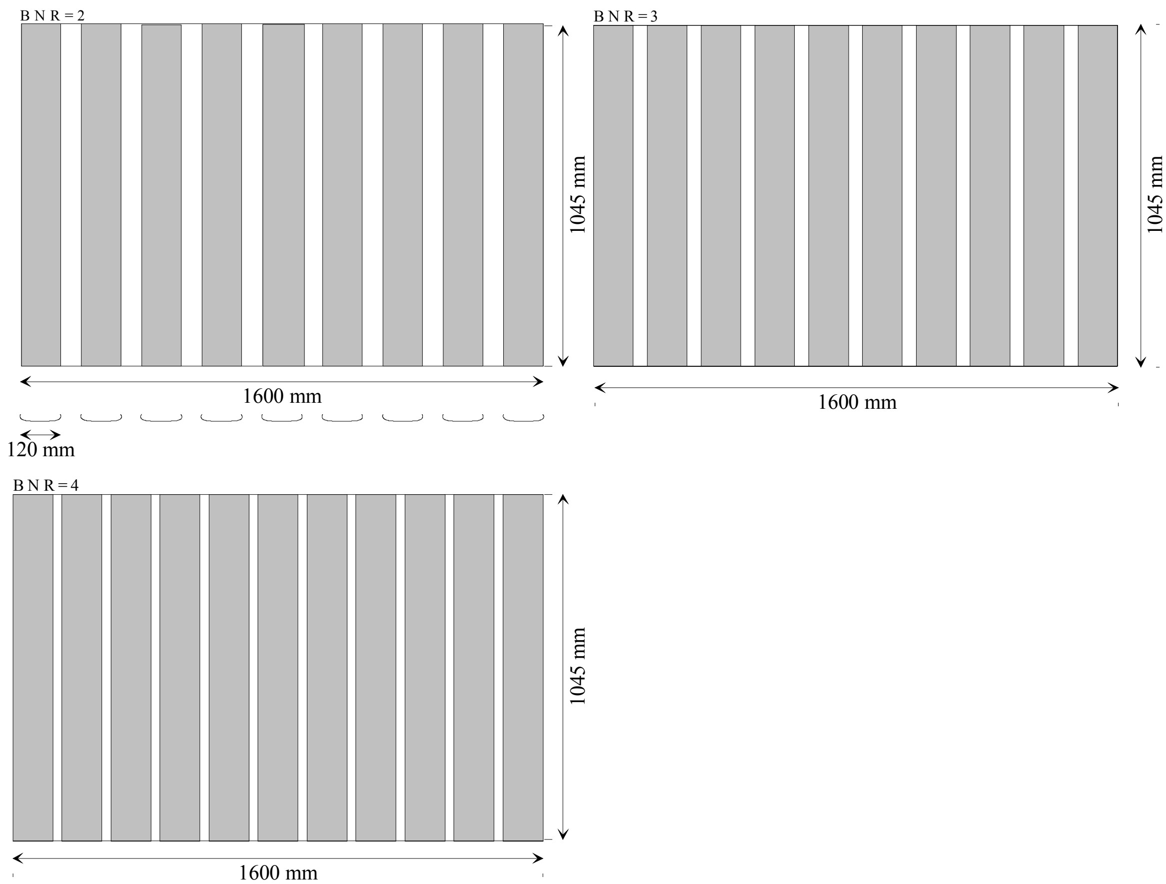

Fig. 2: Trench bench design and setup, BNR=2-4. Dimensions in mm.

The experiments were performed on both slatted benches and trench bench designs the slatted benches consisting of traditional benches with rounded chimney type perforations openings and the trench benches with trenches to hold the plants.
In the experimental set up the total bench surface area is 1.045×1.6 m and the perforation opening area for the different bench designs (BNR) are given by table 1.

BNR	*Temperature difference interval (ΔT_{in-out}), K*	*Bench design*	*Perforation area %*
1	2.0-5.0	slatted	12.5
2	1.2-4.0	trench	21.4
3	1.7-4.5	trench	12.1
4	2.5-4.3	trench	4.9

Table 1: Different bench designs used in the experiment, perforation area and temperature interval used in the test .

BNR=1 is a commercially developed ebb/flood type bench, for which purpose the perforation edges are tipped and the perforation opening is elevated 35mm over the bench surface, not to loose water trough the perforations. Trench benches of 0.12 m width was also used, with different distances between the trenches, giving the minimum perforation opening area of 4.9, 12.1 and 21.4% of the bench surface area. Instead of simple plastic foil scirts that would be used in the greenhouse, the experimental set up consist of a 40 mm Rockwool and reflective foil insulated plywood box, with open top and bottom. The bottom opening height is approximately 0.1 m and upper opening height is 1.1 m above ground surface. The perforated bench is mounted inside the insulated plywood box at 0.7m. above ground surface. Crosswinds is avoided by the insulated box barriers around the bench, measuring in a closed room (a insulated cooling room) and keeping the temperature in the measuring room and the surrounding rooms at a even temperature of approximately 15-20°C.

Energy supply

Energy input is provided inside the box, by 16 screened incandescent bulbs of 100 W each, placed 100 mm above ground surface and connected to a variotransformer. 3 different levels of heat input setpoint were used: $q_{heat,set}$[W] 150, 300 and 600 W (or 90, 179 and 359 Wm^{-2}). The heat power input q_{heat} was measured with a voltage attenuator network, using the method described in the Datataker 500 manual.

Measurements

The data was collected on a Datataker 500. All the climatical scans are performed simultaneously. 192 different combinations (datapoint) of BNR, PLN, q_{heat} and LAI were used and for each combination temperature difference $\Delta T_{in\text{-}out}$ and air velocity v_{air} (to calculate air flow rate $\dot{V}$ m^3s^{-1}) were measured. Primarily120 measurements are taken over a period of 4 minutes to eliminate the effect of periodic fluctuations (240 measurements have been taken for PLN=2 in a few occasions). Air velocity through the perforations, v_{air} [ms^{-1}], is measured with hotwires LSI type DNE501. The hotwire measures in mV which is transformed into ms^{-1} according to the calibration correlation. The position over the perforations is fixed at a distance of approximately 5 mm± 1mm above the perforation opening upper surface, in the horizontal plane centre of the perforation width ±2 mm. When measuring the air flow velocity on the bench with plants, air velocity is measured simultaneously with LSI-anemometers in 3 different fixed positions spread out over the bench. The measurements of air velocity are taken over two periods of 2 minutes at 6 different measuring positions.

The mean heat power input $\overline{q}_{heat}$ [W] for each datapoint, 120/240 measurements, was calculated. There are 192 different values of $\overline{q}_{heat}$.

The temperature of incoming air, $T_{air,in}$ [K], is measured outside the box at 1 point on each of the box sides, that is 4 points in all, at the upper edge of the bottom opening, 20 mm from the box outer surface 100 mm above the ground. The mean temperature $T_{air,in,mean}$ of incoming air is derived from these 4 measurements. The temperature of out coming air, $T_{air,out}$ [K], is measured in the perforation opening. The temperature measurements are measured with welded tip thermocouples type T and the measurement positions is fixed during all the measurements. The mean temperature of the incoming air temperatures $T_{air,in,mean} - T_{air,out} = \Delta T_{in-out}$. The air humidity, RH., is measured in the perforation opening using a Vaisala Humitter 50Y transmitter. All measurement instruments are calibrated and recalibrated to a reciprocal standard.

Plants

The leaf area index (LAI) are measured destructively using a scanner. The shapes of plants chosen are representative of different canopy structures. 5 different plant shapes were used, PLN, PLN=1: Kalanchöe, PLN=2: Saint Paulia, PLN=3: Ficus "Starlight", PLN=4: Chrysanthemum 1 ct. and PLN=5:Chrysanthemum ct. 3. For each plant shape the plants are positioned and grown to a size to obtain 2-4 different LAI values. For each value of LAI, BNR and PLN the flow velocity were measured and the air flow rate $\dot{V}$ [m^3s^{-1}] calculated at 3 different levels of heat input setpoint

$q_{heat,set}$[W] 150, 300 and 600 W (or 90, 179 and 359 Wm^{-2}). The LAI value is limited by the size of plants that are normally produced on bench installations, typically between 1 and 2. The used LAI values were substantially higher than in a traditional production situation to show how the system is affected by working in extreme situations. It is not possible to arrange the plants position on the bench to obtain similar LAI values for the different combinations of benches (BNR) and plants shape (PLN) because the bench construction obstruct this procedure. There are 54 different values of LAI but the LAI values will to some extent be substituted by a 0/1 variable TYPE (where 0 represents the bench without plants and 1 represents the bench with plants). The verification of this procedure will be presented successively.

Statistical methods

The statistical analysis is aimed to show:

1) Repeatability: homogenity of variance for the different datapoints and regression curves,
2) Effect of LAI: that the slope of the regression lines are independent of the value of LAI (in order to use 0/1 variable instead of the different values of LAI)
3) Effect of the bench design: the ventilation efficiency dependency of the different parameters BNR and PLN (and LAI)) and
4) Model: that it is possible to determine the air flow rate by measuring the temperature difference $\Delta T_{\text{in-out}}$.

Results and Discussion

A statistical analysis of the data show that the STD value of air flow rate and temperature difference varies from 19-47% (mean 26%) and 28-42% (mean 36%) respectively.

The data scatter plots of ventilation air flow rate versus temperature difference at different combinations of BNR and PLN, fig. 1.1-1.4 appendix 1, show a non linear tendency, particularly in the case of BNR=4, and this indicates a discrepancy to the energy balance.

The reason for this is the heated air escaping from beneath the bench confinement, because the pressure difference over the bench exceeds the pressure difference of the heated air inside the bench confinement. In other words, the occurrence of counterflow , and a maximum air flow rate $\dot{V}$ border value is reached. This tendency apparently is impede by a small perforation area. For regulation purposes the determination of coherence between nonlinearity of volume flow vs. temperature difference and perforation area are particularly important. The stagnant ventilation efficiency is decisive to the cost benefit of using perforated benches.

The clusters of datapoints for different values of $\overline{q}_{heat}$ is in most cases superimposing each other indicating that the effect of different LAI values have minor influence on the air flow rate. The following statistical analysis will show if this assumption is valid.

Different regression models of temperature difference $\Delta T_{\text{in-out}}$ /air flow rate $\dot{V}$ have been examined. The data should have intercept in (0,0). According to fig. 1.1-1.4 appendix 1, the regression will have a logarithmic or polynomial type converging towards the maximum air flow rate $\dot{V}$ border value. It is examined weather the data should be transformed by a logaritmic scale to obtain the linearity, or a polynomium should be applied. Running a linear regression on two different models

$$\dot{V} = \beta_0 + \beta_1 \Delta T_{in-out} + \beta_2 \Delta T_{in-out}^2$$
$$\dot{V} = \beta_0 + \beta_1 \ln(\Delta T_{in-out})$$

$$H_{oA} : \dot{V}_{pn} \approx N(\overline{q}_{heat,pn}, \sigma_p^2)$$

we find that the variance of fitting the second order polynomium model gives the best fit. The Sum of Squares (SS) of the polynomium is a factor 1-3.2 less than the equivalent SS of the logarithmic transformed linear model. To check the homogeneity of the clusters of data (not using the polynomial model) the model H_{0A} is applied:

Indices $\dot{V}$: n=1-120, $\overline{q}_{heat}$:p=1-192. In the model notation air flow rate $\dot{V}$ is the dependent variable, N indicates that the data is normal distributed, the first argument in the array is the model consisting of the independent variable $\overline{q}_{heat}$ (and coefficients if a estimate is to be determined) and the second argument σ^2 is the variance. The data is assumed independent.
To determine if the variance of the different datapoints (not using the regression model) is homogeneous in model H_{0A} the one-factor Bartlett analysis is used where $\dot{V}$ is the dependent variable. The result is a (Chi-Square) $\chi^2(191)=15495$ giving a p-value of less than 0.0001, thus homogeneity of variance for the different datapoints is accepted.
We use the Bartlett (multifactor) variance analysis to check the assumption that the variance for the different regression curves in the second order polynomial model is homogeneous. The model tested is therefor given by H_{0B}

Indices BNR:i=1-4; PLN: j=1-5, LAI: k=1-60, PLN01:g=1-2, $q_{heat,set}$: l=1-3, ΔT_{in-out} :m=1-120, $\dot{V}$: n=1-120, $\overline{q}_{heat}$:p=1-192. The LAI variable is later transformed into the 0/1 variable PLN01 (2

$$H_{oB} : \dot{V}_{ijkm} \approx N(\beta_{1ijk} \Delta T_{in-out,ijkm} + \beta_{2ijk} \Delta T_{in-out,ijkm}^2, \sigma_{ijk}^2)$$

variables instead of the 60 different values of LAI). The factors are BNR, LAI (or PLN01) and PLN. In the model notation air flow rate $\dot{V}$ is the dependent variable, N indicates that the data is normal distributed, the first argument in the array is the second order model where temperature difference ΔT_{in-out}, is the independent variable, β_1 and β_2 is the coefficients ($\beta_0=0$ because the regression have a forced intercept through (0,0)) and the second argument σ^2 is the variance.
From data of a regression of the second order polynomial regression on each combination of BNR, LAI and PLN it is possible to perform the Bartlett test , (B.Jørgensen, 1993) to determine the homogeneity of variance of the different regressions of the second order polynomial model.
Assuming the approximation

$$B(d) \approx \chi^2(k-1)$$

where k is the number of datapoints and the Bartlett number:

$$B(d) = \frac{Q(d)}{C}$$

where

$$C = 1 + \frac{1}{3(k-1)} \left\{ \frac{1}{f_i} - \frac{1}{f_+} \right\}$$

$$Q(d) = f_+ \log \frac{d_+}{f_+} - \sum_{i=1}^{k} f_i \log\left(\frac{d_i}{f_i}\right)$$

and f_i is the degrees of freedom of the residuals for the datapoint i and $f_+ = f_1 + ... + f_k$ and d_i is the sum of squares of the residuals for the datapoint i and $d_+ = d_1 + ... + d_k$.
The B(d) value is 9330, (Q(d)=9339, C=1.001, $d_+/f_+=2.38*10^{-5}$) which should be compared to a (Chi-Square) $\chi^2(63)=82.53$. Thus B(d)> χ^2. (The B(d) value in the given χ^2 distribution gives a p-value of less than 0.005). Small p-values show discrepancy to the original model. Therefor homogenity of variance of the data is accepted.
Assuming homogenity according to the Bartlett analysis a regression following the model H_{1a} is accepted:

$$H_{1a} : \dot{V}_{ijkm} \approx N(\beta_{1ijk} \Delta T_{in-out,ijkm} + \beta_{2ijk} \Delta T^2_{in-out,ijkm}, \sigma^2)$$

For each combination of BNR and PLN it is evaluated weather the regression lines with plants LAI≠0 have the same slope. Each combination of BNR and PLN have 2-4 different lines (from the different values of LAI≠0). Testing the model H_{2a} against H_{1a}:

$$H_{2a} : \dot{V}_{ijm} \approx N(\beta_{1ij} \Delta T_{in-out,ijm} + \beta_{2ij} \Delta T^2_{in-out,ijm}, \sigma^2)$$

and using the F-test to evaluate the results, assuming that it is the model H_{2a} tested against H_{1a}, the F(y) is calculated using

$$F(y) = \frac{(D_{2a} - D_{1a})/(f_{2a} - f_{1a})}{(D_{1a} / f_{1a})}$$

where D_{1a} and D_{2a} is the sum of squares (SS) of deviance, f_{1a} and f_{2a} is the degrees of freedom (DF) of model H_{1a} and H_{2a}, respectively.
The test (F-test) show that 88.3% of the lines have a 60% probability that the slope of the lines is the same (for the given combination of BNR and PLN). 68.3 % of the lines have over 70% probability, 41.6 % have over 80% probability and 25% have over 90% probability. Although there are a few lines that fall below 60% probability, the hypothesis H_{2a} that the curves (for each combination of BNR and PLN) of different values of LAI are identical is generally accepted. To evaluate weather the slope of the regression on benches with or without plants are different the new variable PLN01 is used, 0 being no plants and 1 being plants with different values of LAI (the effect of leaf density LAI having just been tested out of the model).
To include the new variable the model H_{1b} are:

To evaluate weather the regression lines are independent on plants or not the model H_{2b} is tested against H_{1b}.

$$H_{1b} : \dot{V}_{ijgm} \approx N(\beta_{1ijg} \Delta T_{in-out,ijgm} + \beta_{2ijg} \Delta T^2_{in-out,ijgm}, \sigma^2)$$

$$H_{2b} : \dot{V}_{ijm} \approx N(\beta_{1ij} \Delta T_{in-out,ijm} + \beta_{2ij} \Delta T^2_{in-out,ijm}, \sigma^2)$$

The test show that the difference between benches with plants or not are not significant, 90% have over 60% probability that the lines are identical, 77.5% have over 70% probability, 62.5% have over 80% probability and 10% have over 90% probability. Thus we accept the model H_{2b}, although a few lines fall below 60% probability.
Untill now only the model significance of plants on the bench have been tested. It is difficult to say what the significance of plants are without knowing the significance of the other factors. We therefor perform a factor analysis on the different factors BNR with 4 levels, PLN with 5 levels and

PLN01 with 2 levels each with 360 (720 for PLN=2) replications and the relevant interactions. (The interactions between PLN and PLN01 are not relevant and adds no extra information to the model). The full initial model is:

$$\dot{V} = \Delta T_{in-out}$$
$$+ \Delta T_{in-out}^2 * PLN$$
$$+ \Delta T_{in-out}^2 * PLN01$$
$$+ \Delta T_{in-out}^2 * BNR$$
$$+ \Delta T_{in-out}^2 * BNR * PLN$$
$$+ \Delta T_{in-out}^2 * BNR * PLN01$$

The factor analysis show that the factor interactions between BNR*PLN01 are not significant. Removing the least significant factor (eq. the interaction factor BNR*PLN01) from the model the factor PLN becomes insignificant compared to the other factors. Consecutively removing the least significant factor the result of the factor analysis is therefor that BNR is the foremost dominant factor thus the final model H_3 is only dependent on BNR. From the SS of the error (the part of the data that is not interpreted by the model) it is possible to evaluate weather the reduction in factors in the model have significant influence on the sum of squares of deviations (residuals). The change in the share of residuals to the model that are contributed by the error is changed from 3.73 to 4.08 that is a increase in 9% from the initial model to the one-factor final model. That is a insignificant change.

$$H_3 : \dot{V}_i \approx N(\beta_{1i}\Delta T_{in-out,i} + \beta_{2i}\Delta T_{in-out,i}^2, \sigma^2)$$

This means that the ventilation efficiency is not affected by the increase in plant canopy on the bench or the plant shape but primarily by the bench design (type). Performing a regression on the second order polynomial model H_3 for the different bench designs the model estimation is shown in table 2.

Air flow rate				*Model:* $\dot{V} = \beta_2 * (\Delta T_{in-out})^2 + \beta_1 * \Delta T_{in-out} + \beta_0$		
BNR	$\dot{V}_{mean}$	*Interval* (ΔT_{in-out})	*Perfora area*	β_2*-coefficient*	β_1*-coefficient*	*Root* $MSE * \dot{V}_{mean}^{-1}$
	m^3s^{-1}	K	%			
1	0.0532	2.0-5.0	12.5	-0.00137	0.0212	0.104
2	0.0699	1.2-4.0	21.4	-0.00392	0.0378	0.139
3	0.0560	1.7-4.5	12.1	-0.00192	0.0253	0.104
4	0.0294	2.5-4.3	4.9	-0.000447	0.00877	0.0759

Table 2: Flow coefficients β_1 and β_2 of square model of the volume flow. $\dot{V}$ [m^3s^{-1}] expressed by the air temperature difference ΔT_{in-out} [K] between the intake and outlet temperature. Coefficient β_0=0 (intercept 0,0). .

The model in table 2 is only valid in the stated interval. Bench design (BNR) 1 is a perforated bench design and bench design 2.3 and 4 is trench bench designs. Root MSE (Mean square)* $\dot{V}_{mean}^{-1}$ of residuals show weather the model is qualitatively acceptable. Only the value for BNR=2 indicate that the model have some fitting problems for this bench design. The model in table 2 can be used to determine the air flow rate from a measurement of temperature difference over the bench.

Conclusion

A second order polynomial model have been applied to determine the correlation between temperature difference over the bench and air flow rate. The test performed show that the plant shape and leaf area index (LAI) of plants on the bench have little influence on the vertical ventilation flow of the perforated bench. The most important factor of the ones tested is the bench design.

The experiments show that having determined the bench characteristic flow coefficients the ventilation volume flow is easily predicted for each bench design by measuring the temperature difference over the bench confinement. Further analysis will show if this is also the case in a authentic greenhouse environment where factors as local flow regimes, rapid changes in radiation and non uniform climate conditions in different parts of the greenhouse is liable.

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Notation

Symbol	**Description**
A_{box}	Box + bench surface area, m^2
BNR	Bench design, -
c_p	Heat capacity air, $kJkg^{-1}K^{-1}$
g	Force of gravity, ms^{-2}
H	Skirt vertical height, m
LAI	Leaf Area Index , -
Δp	Pressure difference, Nm^{-2}
PLN	Plant shape, -
PLN01	Plant binary variable, -
$\bar{q}_{heat}$	Mean value heat power, W
q_{heat}	Supplied heat power, W
$q_{heat,set}$	Heat power setpoint, W
q_{loss}	Heat power loss, W
RH	Relative humidity, %
$T_{air,in}$	Incoming air temperature, K
$T_{air,in,mean}$	Mean incoming air temperature, K
$T_{air,out}$	Outgoing air temperature, K
ΔT_{in-out}	Temperature difference incoming-outgoing, K
ΔT	Temperature difference inside/outside, K
$\dot{V}$	Ventilation air flow rate, m^3s^{-1}
v_{air}	Air velocity through perforation centre, m^2s^{-1}
Greek letters	
β	Volumetric thermal expansion coefficient, K^{-1}
ρ	Air Density, kgm^{-3}
λ	Conduction coefficient, $WK^{-1}m^{-2}$
Subscripts	
Statistical notation	
β	Model coefficient
σ^2	Variance
g	PLN01
i	BNR
j	PLN
k	LAI
l	q_{heat}
m	ΔT_{in-out}
N	Normal distribution
n	$\dot{V}$
p	$\bar{q}_{heat}$
TYPE	binary variable for plants

Appendix 1

Scatterplots of the air flow rate $\dot{V}$ (m^3s^{-1}) vs. the temperature difference $\Delta T_{in\text{-}out}$ (K) majority of different bench designs BNR and plant shape PLN used in the experiment.

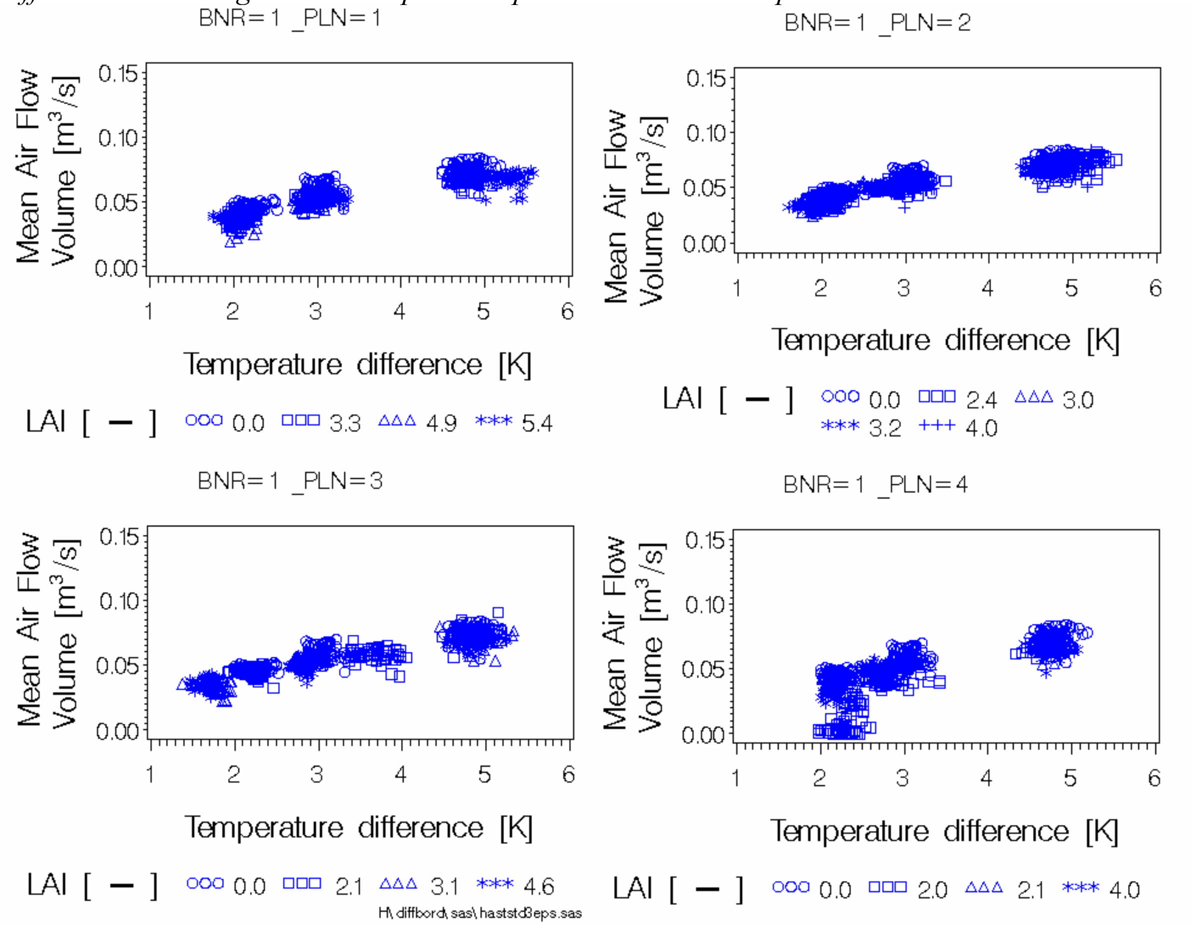

Fig. 1.1: Scatterplots of the air flow rate $\dot{V}$ (m^3s^{-1}) vs. the temperature difference $\Delta T_{in\text{-}out}$ (K) for bench designs BNR=1 and plant shape PLN=1-4 at different leaf area index (LAI).

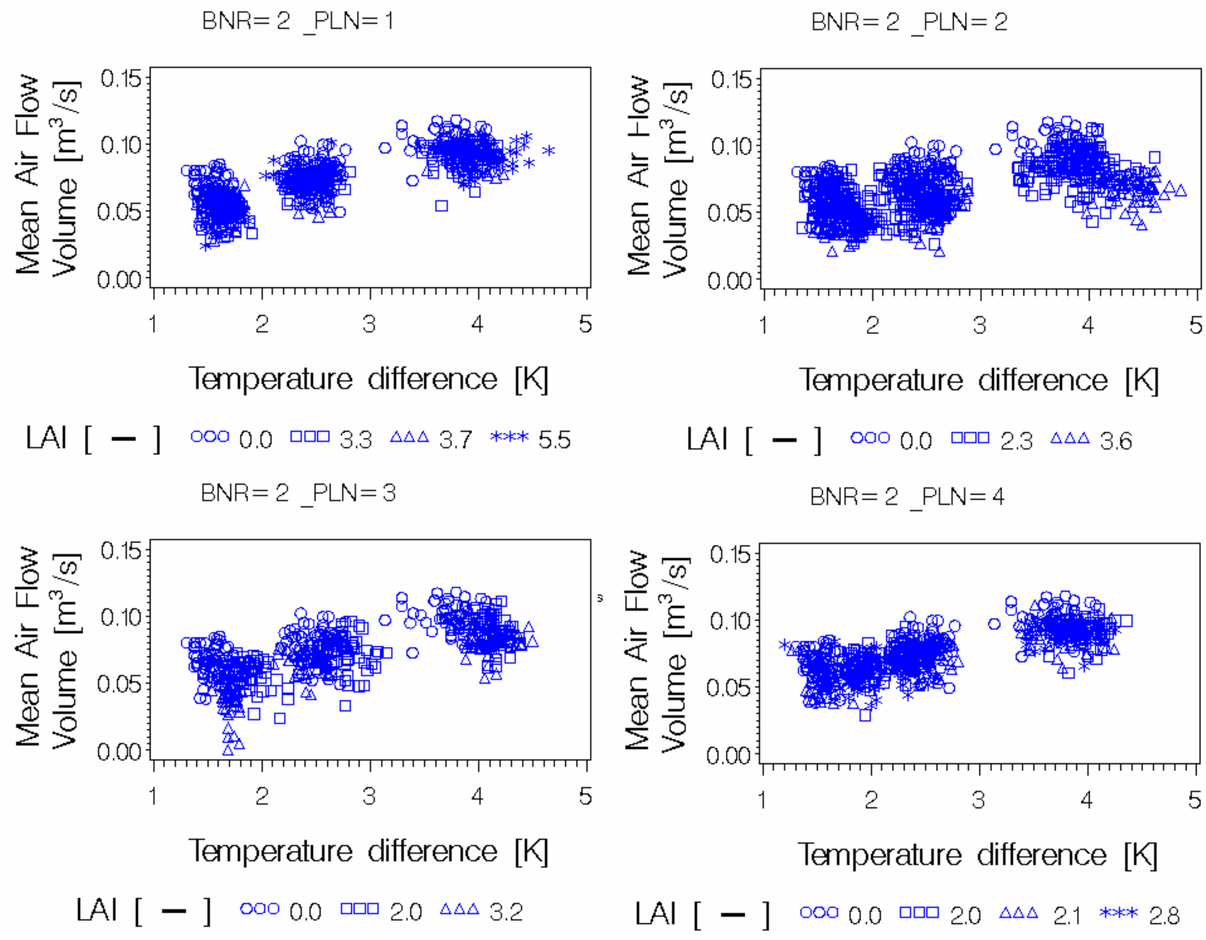

Fig. 1.2: Scatterplots of the air flow rate $\dot{V}$ (m^3s^{-1}) vs. the temperature difference $\Delta T_{in\text{-}out}$ (K) for bench designs BNR=2 and plant shape PLN=1-4 at different leaf area index (LAI).

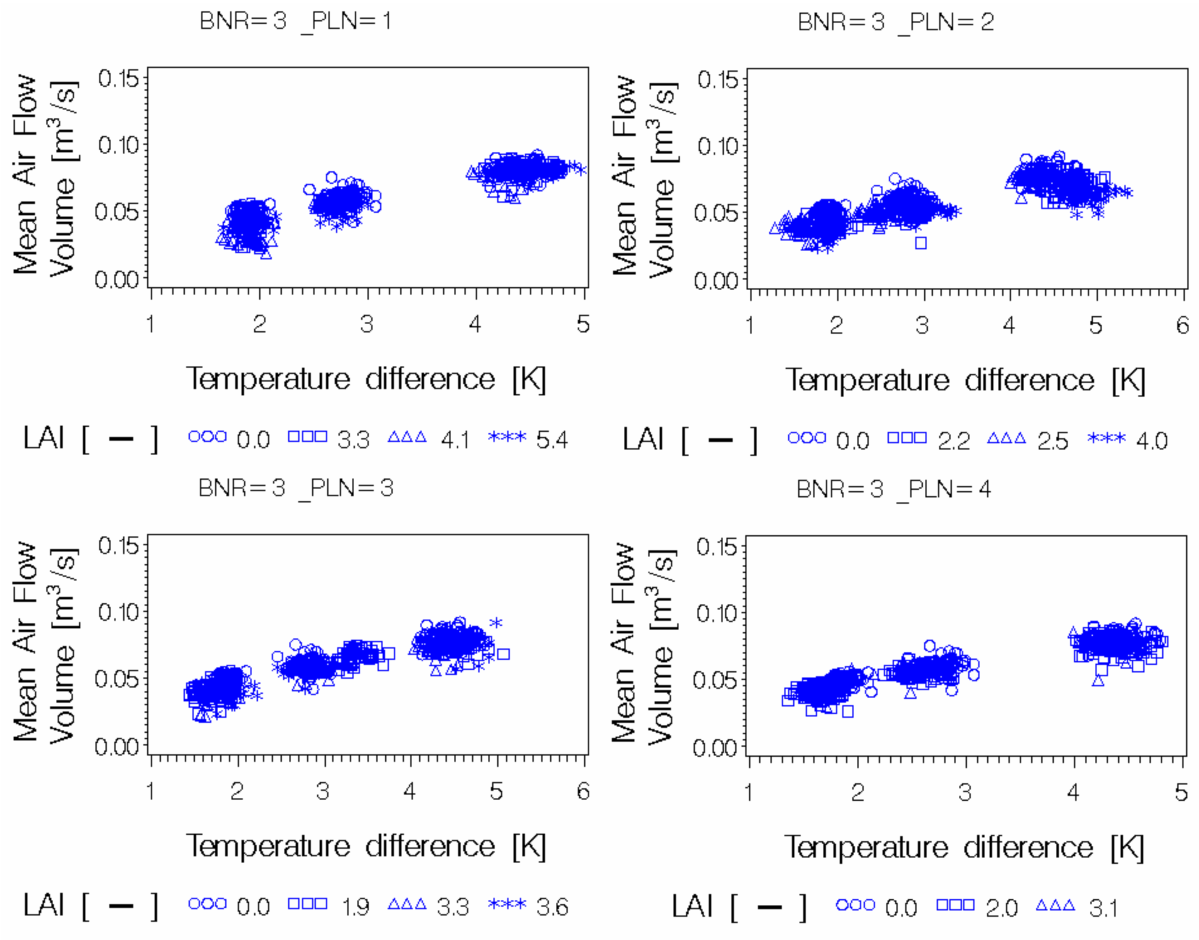

Fig. 1.3: Scatterplots of the air flow rate $\dot{V}$ (m^3s^{-1}) vs. the temperature difference $\Delta T_{in\text{-}out}$ (K) for bench designs BNR=3 and plant shape PLN=1-4 at different leaf area index (LAI).

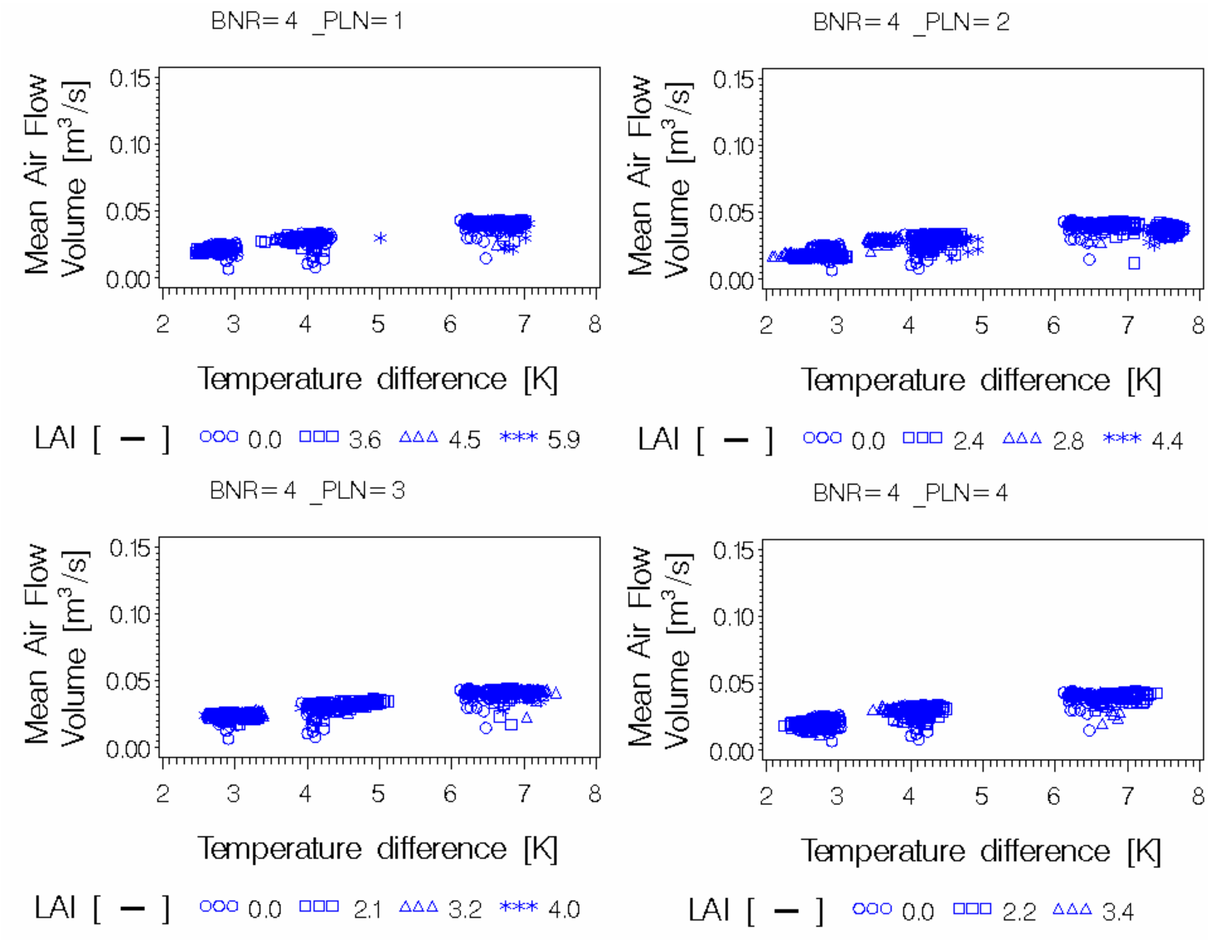

Fig. 1.4: Scatterplots of the air flow rate $\dot{V}$ *(m^3s^{-1}) vs. the temperature difference* $\Delta T_{in\text{-}out}$ *(K) for bench designs BNR=4 and plant shape PLN=1-4 at different leaf area index (LAI).*