JET MOMENTUM CRITERIA FOR INLET CONTROL TO REDUCE WIND EFFECTS ON THE AIR DISTRIBUTION IN A SIDE-WALL-INLET VENTILATION SYSTEM

Guoqiang Zhang[1] and Sung-Hyoun Lee[2]

[1]Department of Agricultural Engineering, Research Centre Bygholm
Danish Institute of Agricultural Engineering, DENMARK
[2]National Agricultural Mechanization Research Institute, KOREA

ABSTRACT

A problem in a livestock building ventilated in the system with wall inlet at two sides is wind effects to the indoor air flow patterns. The in-proper inlet jet penetration profiles may cause draught at occupied zone and unnecessary stress of animals. The wind effects on such a system can be reduced by applying windbreak to the inlets from design point of view. However, a remain issue is if the effect could be reduced by regulating inlet opening and how to perform the control operation.

The hypothesis of this study is that the unbalance of the incoming air flows from the two side wall, which caused by wind effects, can be overcome by adjusting the inlet openings to maintain the balance of the jet momentum of the both incoming air jets. If that is true, inlet jet momentum criteria should be able to applied in a control system to maintain the similar inlet jets from both side walls.

A 1/10 scale model of a livestock building with both-side wall inlet was used in the investigation in laboratory conditions. In the experiments, the model was placed at a wind board with simulated wind speed of 0-3.5 m/s across the model. Different ventilation rates, inlet openings and operating pressures were applied. The experimental results great supported the above hypothesis. It is concluded that if the jet momentum ratio is maintained to unity under the wind condition the jet penetration depths from two sides will be balanced. The jet momentum criteria can be applied to control side wall inlets to reduce wind effect on the indoor air distribution.

KEYWORDS

Air flow pattern, Jet, Inlet control

INTRODUCTION

A problem in a livestock building ventilated with the system having wall inlets at two sides is the wind effects to the indoor air distribution. A cross wind effects can cause in-taking air velocity at windward increasing and at leeward decreasing, and even a cross ventilation. Consequently, the symmetric air jet trajectories are distorted. These in-proper inlet jet penetration profiles will cause unnecessary draught at occupied zone and animal stress. Strøm and Morsing (1996) showed the wind effects on such a system can be reduced by applying windbreak to the inlets from design point of view. However, a remain issue is if the effect could be reduced by regulating inlet opening and how to perform the control operation.

Inlet jet momentum has been proved a important factor effecting jet penetration in a confined ventilated space (Barber et. al., 1982; Nielsen and Möller, 1987; Adre and Albright, 1992). Studies on thermal buoyant air jets has also indicates that the inlet jet momentum as a key factor in Archimedes Number against the buoyant force in the air space (Koestel, 1955; Mullejans, 1966; Baturin, 1972; Zhang et. al. 1992, 1996). These studies showed that increasing the inlet jet momentum will reduce the thermal buoyant effect on inlet jet trajectory. The same principle could be applied to control the inlet jet momentum to minimize wind effect on a ventilation system. Brockett and Albright (1984, 1987) developed a control program that calculates a required ventilation rate and then adjusts vent openings to achieve uniform air intake in a natural ventilated building. However, the program was only verified by a computer simulation.

This study presented in this paper was conducted with 1/10 scale model of a livestock building to maintain the uniform air flow pattern of both-side inlet and to reduce wind effects on the ventilation system. The hypothesis is that the unbalance of the incoming air flows from the two side wall, which caused by wind effects, can be overcome by adjusting the inlet openings to maintain the balance of the jet momentum of the both incoming air jets. If that is true, inlet jet momentum criteria should be able to applied in a control system to maintain the similar inlet jets from both side walls.

SYMBOLS

A	inlet opening area, m^2
h	inlet opening height, m
k	coefficient
l	inlet length, m
M_j	inlet jet momentum, $kg \cdot m/s^2$
Δp	operating pressure, Pa
U	airflow rate, m^3/s
v_o	inlet velocity, m/s
w	wind velocity, m/s
ρ	air density, kg/m^3

Subscripts:

a	actual geometric opening
e	effective
l	leeward
o	at inlet opening
w	windward

MATERIAL AND METHODS

Theoretical Basis

The hypothesis of inlet control is that the incoming air flow from the both side wall inlets maintain balance (symmetric patterns) if the inlet jet momentum is kept in equal, i.e., the ratio of the two side wall jet momentum is one. The jet momentum in design condition (a defined operation pressure at wind speed = 0) could be used as the reference value for control.

Ventilation airflow through a mechanical negative pressure system is caused by the pressure difference over the inlets. Under no wind condition, the pressure difference is induced by the system including fan, inlet and the building. Under wind effect, the pressure difference resulted by the system and wind.

$$\Delta p_{ow} = \Delta p_o + k_w \cdot w^2 \quad (1)$$

$$\Delta p_{ol} = \Delta p_o - k_l \cdot w^2 \quad (2)$$

About the sign of the wind coefficients in the above equations, positive is assumed for the effect of increasing in-take air rate and negative for the effect of decreasing.

As long as w equal to zero, the pressure differences across the two side wall is the same:

$$\Delta p_{ow} = \Delta p_{ol} = \Delta p_o \quad (3)$$

At the required ventilation air flow rate, U, which determined by heat balance of in a practical system to maintain a desired temperature or by other gas concentration, and an operating pressure (Δp), the jet momentum (M_j) of each side in-taking air is proportional to the effective opening height (h) of the inlet and squared inlet velocity (v_o^2) if w=0.

$$\begin{aligned} & M_j (= M_{jw} = M_{jl}) \\ & = v_o \cdot m / 2 = \rho_o \cdot v_o^2 \cdot h_e \cdot l \end{aligned} \quad (4)$$

Since inlet length, l, at each side wall is constant, we have,

$$M_j \propto v_o^2 \cdot h_e \quad (5)$$

Assume $\rho_{ow} = \rho_{ol}$, the two jet momentum will be equal, if

$$v_o^2 \cdot h_e = v_{ow}^2 \cdot h_{ew} = v_{ol}^2 \cdot h_{el} \quad (6)$$

or

$$h_{ew} / h_{el} = v_{ol}^2 / v_{ow}^2 (= \Delta p_l / \Delta p_w) \quad (7)$$

Set $H_e = h_{ew} / h_{el}$ and $V = v_{ow} / v_{ol}$ (or $P = \Delta p_w / \Delta p_l$), it will be,

$$H_e = 1 / V^2 = 1 / P \quad (8)$$

The ventilation flow rate:

$$U = 2 \cdot v_o \cdot h \cdot l = v_{ow} \cdot h_w \cdot l + v_{ol} \cdot h_l \cdot l \quad (9)$$

The operating pressure Δp_o should be larger than $k_w \cdot w^2$ to avoid a negative inlet velocity at leeward side. Therefore, a high value of Δp_o may be needed for strong wind effects.

Control strategy

A controlled ventilation system in livestock generally operated to maintain a desired indoor air temperature based on regulating the ventilation air flow rate U which is a function of differential pressure Δp_o, and inlet opening h_o (under condition of w=0), and consequently inlet jet momentum M_{jo}. Under wind effect condition, v_{ow} increases and v_{ol} decreases. To maintain the same jet momentum and the desired flow rate to maintain the heat balance, the inlet opening should be controlled according to Equations (8) and (9).

Experiments

The experiments were carried out with a 1/10 scale model placed at the wind table (Figure 1), Air Physics Lab, DIAS.

Experiment 1: The first experiment was to characterise the vacuum exhaust ventilation unit and the inlets at non-wind conditions. Inlet air velocities, operating pressures and airflow rates were measured under six operation stages of the exhaust unit (power in 300-1500W) and two inlet openings (6.3 and 3.2mm).

Experiment 2: In order to find the outside wind effects, the outside wind velocity varied for 0.5, 1.0, 1.5, 2.0 m/s when inlet opening of both-side were fixed 6.3mm. The acquisition data were inlet velocity of both-side, differential pressure, outside wind velocity, inlet airflow pattern of both-side.

Experiment 3: The inlet opening height at windward were adjusted to overcome wind effects when the leeward inlet opening height was fixed. The air flow pattern in this time were balanced in both-side opening of scale model. The acquisition data were inlet velocity of both-side, differential pressure, outside wind velocity, inlet airflow pattern of both-side.

Scale model

The 1/10 scale model was made of 10mm thick Plexiglas. The inside dimensions were 1.05m deep, 0.5 m wide, 0.25 m side-wall height and 0.50 m ridge height. The inside volume of the model was $0.1863 m^3$. Inside air was exhausted from the model through a 30mm tube in the roof connected to a vacuum unit that could be adjusted to provide different airflow rates.

The model was fitted with a 10 mm high continuous inlet slot under the eaves in both side-walls. A 35mm wide, adjustable, bottom hinged flap was installed inside the slot. The flap was varied inlet opening from 2 mm to 8.3 mm during the experiments. In order to observe the inlet airflow pattern of both-side was used smoke generator and the backside of the scale model was painted the black color for visual effect.

Velocity Sensors

Two semiconductor velocity sensor was used in the experiment to measure the inlet velocity of each side. The output range of the sensors were from 0 to 20mA represent velocity from 0 to 10m/s. The velocity-current curve of the sensors were achieved by a pre-calibration using a hot bulb velocity sensor as reference (Lee and Zhang, 1997).

Wind table

The wind table consisted of an axial fan and mesh screen which delivered air on a horizontal surface adjacent to a wall. The diameter of an axial fan was 1.2m and maximum revolution per minute was 450. The maximum outside velocity in the place of the outside velocity sensor for the measurement was about 3.6~4.0 m/s when the revolution per minute of an axial fan maximized. The mesh screen was used to stabilize the wind delivered through the fan. Basically, the wind table was a low speed, open circulation wind tunnel with one wall and the top surface removed from the working section.

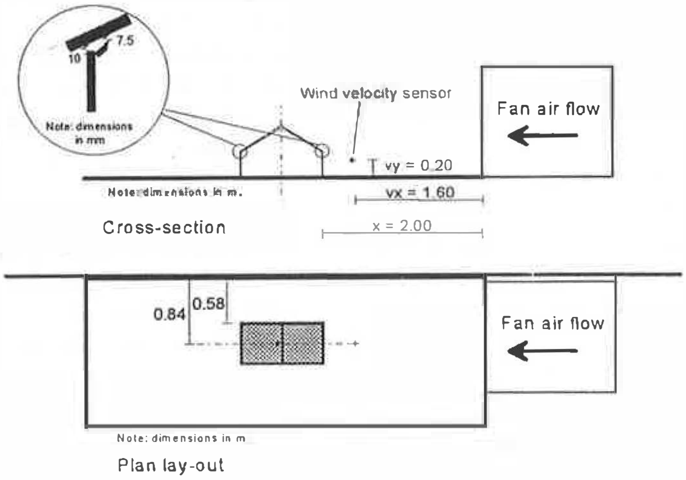

Figure 1 Layout of wind-table and scale model including details of the design for the experiment and the location of the scale model on wind table

The velocity of the air delivered by the fan decreased with the distance from the fan, except within the core where it theoretically remained constant for some distance. A portion of the wind table was used as the working section where the scale model was placed for wind experimentation. The scale model was placed in the middle of the wind table for fan airflow. The position of the scale model on the wind table was as showed in Figure 1.

Data acquisition

The inlet velocity sensor was placed in the middle of inlet opening. The measured data were recorded on a computer, scanning two sensor point every second. Average values were calculated every 30 second and saved. Each measurement was conducted every 10 minutes. The measurement value used for analysis was a average value through the 10 minutes. Wind velocity was measured with Dantec N54 velocity analyzer at a point 1.6 m downstream from the front axial fan, 0.4m upstream to the model, and 0.2 m above the wind table. A differential micro-manometer, FC0510, was used to determine the pressure difference between the room air space within the model and the undisturbed air under the wind table. A pitot tube was used to measure the exhausted air flow rates.

Airflow pattern was visualized by using the smoke. Inlet air jet trajectories and flow mixing pattern were drowned on paper according to smoke observation for each experiment.

RESULTS AND DISCUSSION

Inlet discharge coefficient C_d

As combination of the contraction coefficient of an inlet opening and coefficient of friction, the coefficient of discharge is a function of the actual airflow through an inlet(U_o), the gross inlet area and ideal velocity,

$$C_d = \frac{U_o}{A_a \cdot v_o} \tag{10}$$

Where,

$$v_o = \sqrt{\frac{2 \times \Delta P}{\rho}} \tag{11}$$

Defining

$$A_e = \frac{U_o}{v_o} \tag{12}$$

Then,

$$C_d = \frac{A_e}{A_a} \tag{13}$$

Figure 2 showed that a coefficient of discharge(C_d) increase according to increase the exhausted airflow rates in the experiments ranged 20~60 m^3/h. It indicates that the flow in the model is not Re-number independent, the flow similarity is not kept. Therefore, it is worth to consider that the quantitative comparisons of windward and leeward flow parameters could be not representative.

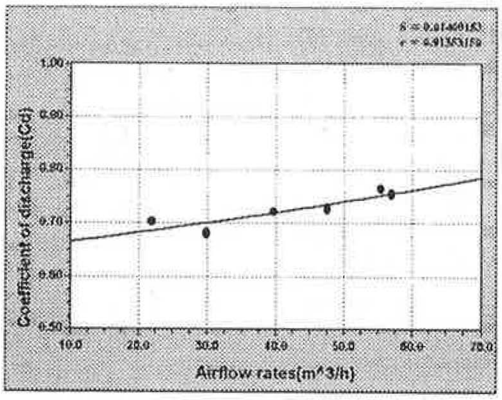

Figure 2 The variation of C_d according to varied air flow rates

Jet momentum ratio

Without wind effect, the velocity was only depended on system operating pressure, which was the same for both sides. Consequently, the recorded inlet air velocities at both side of inlet openings were nearly equal in non-wind conditions as expected. The jet momentum ratio, jet momentum and airflow pattern of both-side according to increased airflow rates is given in Figure 3. The opening area of both-side maintained the same, outside wind velocity nearly equal to 0 m/s. The jet momentum of both-side increased following airflow rate increasing. While, the jet momentum ratio (M_{jl}/M_{jw}) was maintained nearly 1. The observed inlet airflow pattern (Jet trajectories) were also in balance.

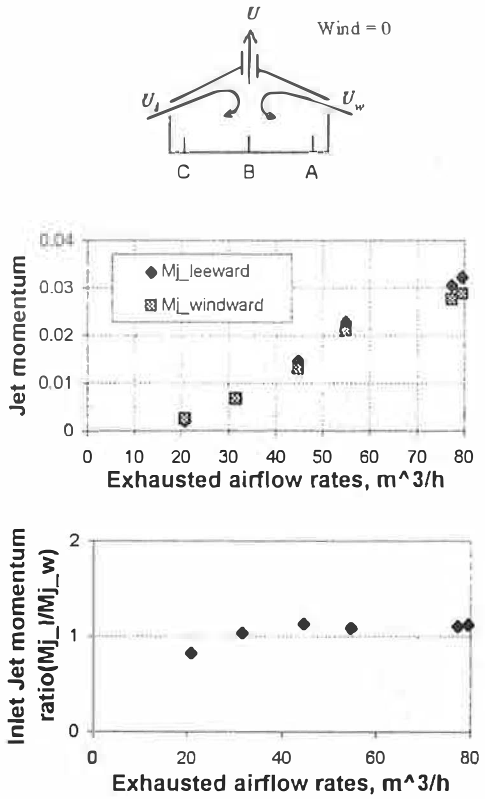

Figure 3 Jet momentum, jet momentum ratio and air flow pattern of both-side inlet opening. Wind velocity = 0 m/s, inlet opening $h_w = h_l = 6.3$ mm.

Under wind effects, the air velocity and airflow rate through the inlet of the windward increase and the air velocity and airflow rate through the inlet of the leeward decreased following wind speed. Remaining the inlet opening unchanged, jet momentum of the inlet were changed as results of inlet air velocity varied. Therefore, unbalanced penetration depths of the two inlet air jets appeared.

Figure 4 illustrated the variation status of penetration depth of inlet air jet under wind effects without inlet control. In a constant airflow rate of the exhaust units, the penetration depth of the air jet in the windward increased and in leeward decreased as wind velocity increased. If the inlet airflow rate of windward higher than exhausted airflow rate, part of air from the windward inlet will escape through the leeward inlet as cross ventilation, Figure 4(3).

The inlet jet momentum ratio is directly related to the airflow rates of the exhaust unit (operating pressure) and the wind velocity when the inlet openings of both-side are the same.

The jet momentum ratio versus wind velocity is presented in figure 5 according to different exhausted airflow rates (operation pressure). It is clear that M_{jl}/M_{jw} decreased with increasing of wind velocity. The effects were more significantly in lower exhausted airflow rates. This results indicated that the wind effects to the system may be reduced by increasing operating pressure level.

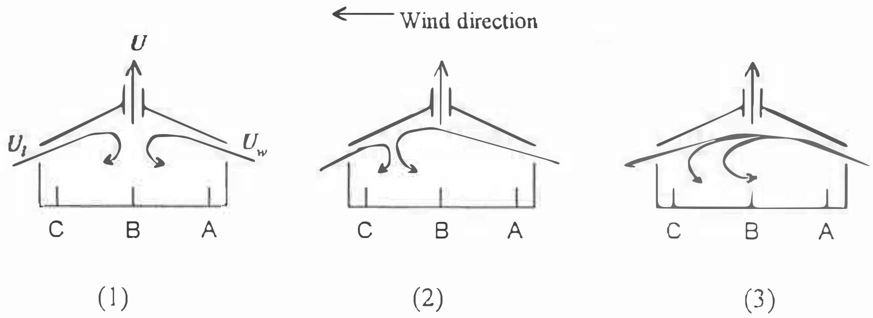

Figure 4 The variation of the penetration depth of the inlet airflow according to increase outside wind velocity. If $h_w = h_l$, $U > U_w = U_l$ ...(1), $U > U_w > U_l$ ...(2), $U < U_w$ ...(3).

The balanced penetration depth of inlet air jets may be indirectly controlled by regulating the inlet opening of windward relate to wind velocities. Figure 6 showed that uniform airflow pattern could be achieved by well controlled inlet opening area of both-side with unchanged exhaust airflow rates. Adjusting the inlet opening ratio was actually varying the inlet jet momentum. Reduced the windward inlet opening did assist to maintain the jet momentum ratio (M_{jl}/M_{jw}) around one.

Another factor to maintain a balanced airflow pattern is the system operating pressure. In the carried experiment, the operating pressure was related to the operation stages of the exhaust unit. The effects of by increased wind velocity were reduced by increasing the operating pressure (airflow rates).

The smoke visualisation showed that when the jet momentum ratio (M_{jl}/M_{jw}) was maintained around level of one, the airflow pattern was in balance from the both sides.

This results indicate that (1) the jet momentum ratio of the inlet openings can be used to represent the total effects of outside wind velocity and exhausted airflow rates and (2) it could be used as a criteria to control the ventilation system for an uniformed airflow pattern to overcome the wind effects. In such a control system, when the wind speed rise above the designed range, the system will decrease the windward inlet opening area and increase the operating pressure to maintain the total ventilation flow rate and the jet momentum ratio within the same range.

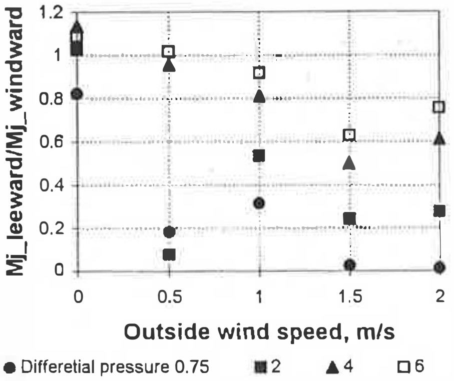

Figure 5 Inlet jet momentum ratio variation following outside wind velocity and operating pressure (exhaust airflow rates). Inlet openings: $h_w = h_l$.

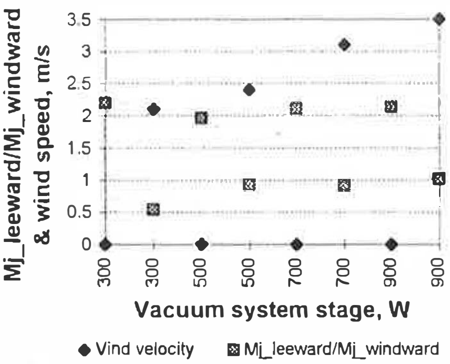

Figure 6 The inlet opening height adjusted to prevent the wind effects and maintain the inlet airflow patterns in balance at test wind speeds. Inlet openings: $h_w = 3.2$ mm, $h_l = 6.3$ mm

The wind effects on the air flow rates at the two side inlets is given in figure 7, where wind speed was 1.5 m/s and the inlet openings were equal in both-side. The exhausted airflow rates was varied from 24 to $74\,m^3/h$. The results showed that the difference of the flow rates from the two sides was reduced by changing the operating pressure. The wind effects was larger when the operating pressure (exhausted airflow rates) was lower.

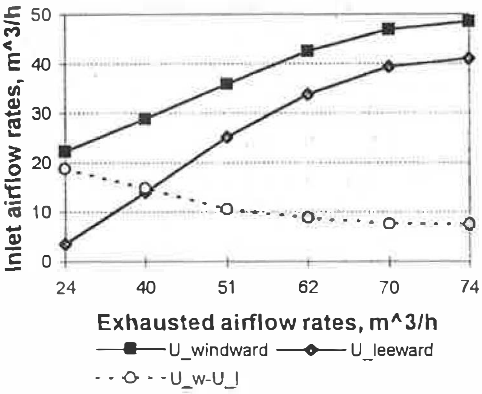

Figure 7 The air flow rates versus the wind speeds accordingly.

This indicates that the windward inlet opening area must be controlled to maintain the uniform air flow pattern in both-side inlet opening. If outside wind velocity increase higher, the inlet airflow rates on windward starts to increase. When the ventilation system was not operated, the airflow rate incoming in leeward should not be existed. As results, this could be achieved the cross ventilation through the leeward inlet opening. Especially, the livestock building with the natural ventilation, the wind effects more higher than the mechanically ventilated building. In this experiments, the airflow rates through both-side is dependent on the exhausted airflow rates, the wind speed of outside when the opening area of both-side equal to same. The airflow in a building is an important factor influencing the distribution of pollution and air temperature.

CONCLUSION

The study conducted with 1/10 scale model of a livestock building was performed for an uniform inlet airflow pattern control criteria. The inlet air velocities and jet momentum at both-side were nearly equal under the conditions of the same openings and without wind. The measured jet momentum ratio (M_{jl}/M_{jw}) was nearly 1 as expected.

Maintained a constant airflow rates for the exhaust units, the penetration depth of the air jet moved from the symmetric position at the centre to leeward side in the room accordingly by increasing the outside wind speed. When the inlet airflow rates of windward was higher than exhausted airflow rates, the leeward inlet became a part of outlets formed as cross ventilation.

The jet momentum ratio were effected by the exhausted operating pressures (airflow rates) and the wind velocity for in-varied inlet openings. It was observed that to adjust inlet jet momentum ratio by varying operating pressure and inlet opening would change the jet penetration depths. When the airflow pattern balance appeared, the jet momentum ratio were closed to 1. This results indicated that the jet momentum of both-side inlet opening could be used to control for uniformed airflow pattern to overcome the effects of the outside wind velocity.

In control practice, the inlet opening area and system operating pressure can be controlled continuously by monitoring inlet air velocities at both side and inlet opening grades.

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