Measurement guideline

# H02
# Investigation of an Air Curtain

FLOW MEASUREMENTS

BMEGEÁTMW03

# Introduction

Air curtains are used to separate two regions of different air temperature or pressure. [1] These are important devices are they can significantly reduce heat loss without limiting accessibility. Such air curtains are found at the entrances of shopping malls, industrial plants and cooling houses. Besides that, air curtains can be used to keep certain areas clean, as they prevent wind from carrying leaves, etc. into the area, and may even stop insects from flying in.

The aim of the measurement is the experimental investigation of such an air curtain using the H02 model setup. The assignment is to vary the input settings and study the resulting air curtains from both qualitative (flow visualisation) and quantitative (calculations) points of view.

Understanding of the assignment requires the knowledge of the momentum theorem [2], planar free jets [3], air curtains [1] and certain measurement procedures and techniques [4]. The reader is referred to the book in the References or any available resource on the topic.

# Important quantities

- $b$ doorway size [m]
- $p_k$ ambient pressure [Pa]
- $p_b$ inner pressure [Pa]
- $\Delta p$ difference of inner and ambient pressure [Pa]
- $\Delta p_d$ jet dynamic pressure [Pa]
- $\rho$ air density [kg/m$^3$]
- $R$ radius of the free jet [m]
- $R_t$ radius of the free jet in the axis [m]
- $s_0$ outlet gap size [m]
- $v_0$ jet initial velocity [m/s]
- $\beta$ inlet angle [°]
- $B$ dimensionless gate size [-]
- $D$ pressure coefficient [-]
- $K$ measured air curtain parameter [-]
- $\widetilde{K}$ air curtain parameter from literature [-]

# Theoretical Summary

## Theory

The air curtain balances the $p_b$ inner and the $p_k$ outer pressure, that results in a $\Delta p$ pressure difference, by the bent streamlines that close the gap of width $b$. In case of bent streamlines, the pressure variation in the normal direction is given by Euler's equation, if force fields are neglected:

$$\frac{v^2}{R} = \frac{1}{\rho}\frac{\partial p}{\partial n} \quad (1)$$

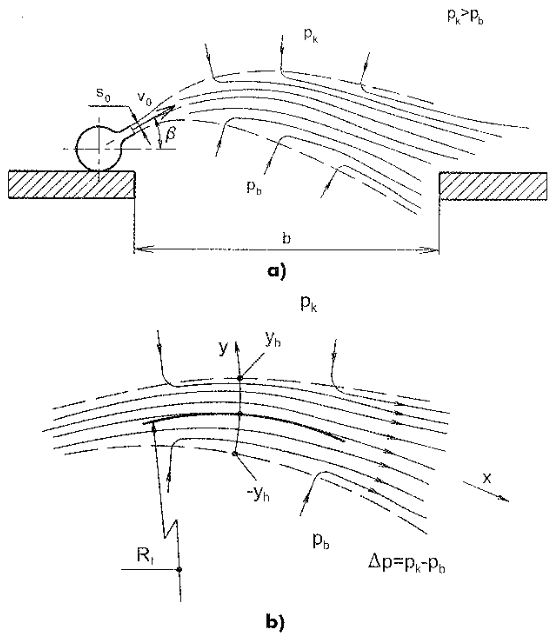


Figure 1. Operation of an air curtain (a), flow cross section (b) [1]

This equation can easily be understood by considering that a force has to act on the free jet to force it onto a curved path. This force originates from the pressure difference.

By separating the variables and introducing a new normal variable $y$ that is perpendicular to the streamlines, has $y = 0$ on the axis of the free jet we get the following expression. Note that the width of the jet extends from $-y_h$ to $y_h$.

$$\int_{p_b}^{p_k} \mathrm{d}p = \int_{-y_h}^{y_h} \rho \frac{v^2}{R} \mathrm{d}y \tag{2}$$

Assume that the curvature of the free jet does not change in the normal direction, meaning that $R = R_t$, the radius on the axis of the free jet, that does not depend on $y$. This is an appropriate assumption since the jet does not spread too much. Integration yields the following:

$$\Delta p = p_k - p_b = \frac{1}{R_t} \int_{-y_h}^{y_h} \rho v^2 \,\mathrm{d}y \tag{3}$$

Using the parameters given at the velocity outlet cross section:

$$\Delta p = \frac{\rho v_0^2 s_0}{R_t} \tag{4}$$

This result means that the radius of curvature does not depend on the streamwise coordinate either, therefore the shape of the air curtain is a circular arc. From simple geometry, the width of the gap is:

$$b = 2\,\mathrm{R_t} \sin\beta = 2 \frac{\rho v_0^2 s_0}{\Delta p} \sin\beta \tag{5}$$

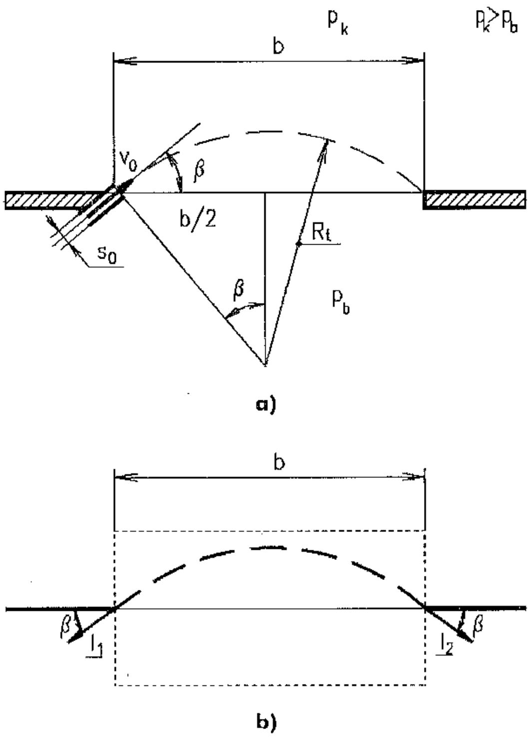


Figure 2. Air curtain geometry (a) and angles and distances required for the momentum equation (b) [1]

Use the theorem of momentum conservation on the control surface in Fig. 2! The flow is steady, body forces are neglected, and therefore the volume integrals have values of 0. Friction is neglected, too. Momentum flux vectors are taken to point outwards from the control surface, while positive pressure forces point inwards. There is no solid body present inside the control surface. The horizontal component of the momentum balance is trivial, while the vertical gives the following:

$$2\,\rho v_0^2 s_0 \sin\beta = \Delta p\, b \tag{6}$$

The expression is reorganized:

$$\frac{b}{s_0} = 2\frac{\rho\, v_0^2}{\Delta p}\sin\beta \tag{7}$$

After that, the following dimensionless quantities are introduced: $B = \frac{b}{s_0}$ and $D = \frac{\Delta p}{\frac{\rho}{2}v_0^2}$, thus we obtain the following theoretical formula:

$$B = \frac{4}{D}\sin\beta \tag{8}$$

However, reality differs from this ideal model. This is taken into account by substituting 4 with a parameter $K$:

$$B = \frac{K}{D}\sin\beta \tag{9}$$

Equation (9) is used to express the value of $K$, that can be calculated using the measured quantities.

Based on earlier measurements, for well-behaving air curtains, this parameter can be estimated depending only on $B$. This empirical value is denoted by $\widetilde{K}$:

$$\widetilde{K} = 1{,}71 + 0{,}0264\,B \qquad (10)$$

Note: Eq (10) is valid if $25° < \beta < 45°$ and $10 < B < 40$.

## Operating states

According to the operation of the air curtain, proper and improper operating states can be observed.

In case of a proper operation state, the free jet sticks to the gate and reaches a stable state. The set $\beta$ angle determines the shape of the free jet, its radius of curvature and the pressure difference between the inside of the model and the ambient pressure. Improper operation state occurs for a non-leaking air curtain when the $\beta$ angle or the $b$ doorway size are too large, and the jet is unable to attach to the gate wall and get a stable curvature. In this case the jet may periodically attach and reattach or straighten out, in which case it is not able to maintain a pressure difference between its two sides.

If the air curtain closed, three different operating states can be set, referred to as non-leaking, inwards-leaking and outwards-leaking. In this context, leaking means the total volume flow rate passing through the air curtain, i.e. it is possible that in some areas there is inwards-leakage, in some others there is outwards-leakage but their sum is zero.

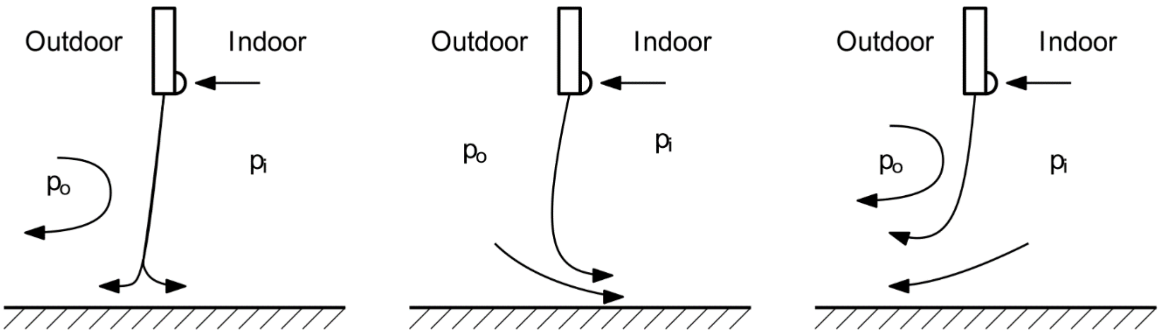


Figure 3. Non-leaking (left), inwards leaking (centre) and outwards leaking (right) air curtains.
Figure was created by Balázs Kiss.

In a non-leaking state there is no leakage flow. If the leakage flow rate is small compared to the jet flow rate, the proper, nominal operation state can be assumed and the formulae for proper operation states can be applied.

If the leakage flow rate is large the air curtain is in an improper operation condition, since the momentum rates are significantly different from those discussed in the theory. In case of strong inwards leakage the jet bends inwards and air leaves through the suction pipe and the pressure values are to be examined. In case of strong outwards leakage flow the jet does not bend, since the pressure values equalize themselves via the inflow through the suction pipe. The flow rate values are of interest in this case.

# Measurement setup

The measurement setup consists of the following:

- blower
- adjuster coil
- measurement device, containing

  - jet outlet with adjustable angle
  - gate with adjustable size
  - inlet orifice (closable)
  - wall pressure taps in the chamber
  - wall pressure taps on the gate wall
- Pitot-probe
- digital manometer
- smoke generator
- laser sheet

During the measurement, different volume flow rates can be set with the adjuster coil. The air from the blower enters the measurement device through the gap, then the free jet is formed, that can close the doorway. By closing the inlet orifice, a non-leaking air curtain can be constructed, while if it is left open, an outwards leaking air curtain is obtained. In case of leakage, the leakage flow rate can be calculated from the pressure drop measured on the inlet orifice. Through the pressure outlets, the pressure difference between the inside and the atmosphere can be recorded, while the pressure outlets above the doorway give information about the reattachment of the air jet.

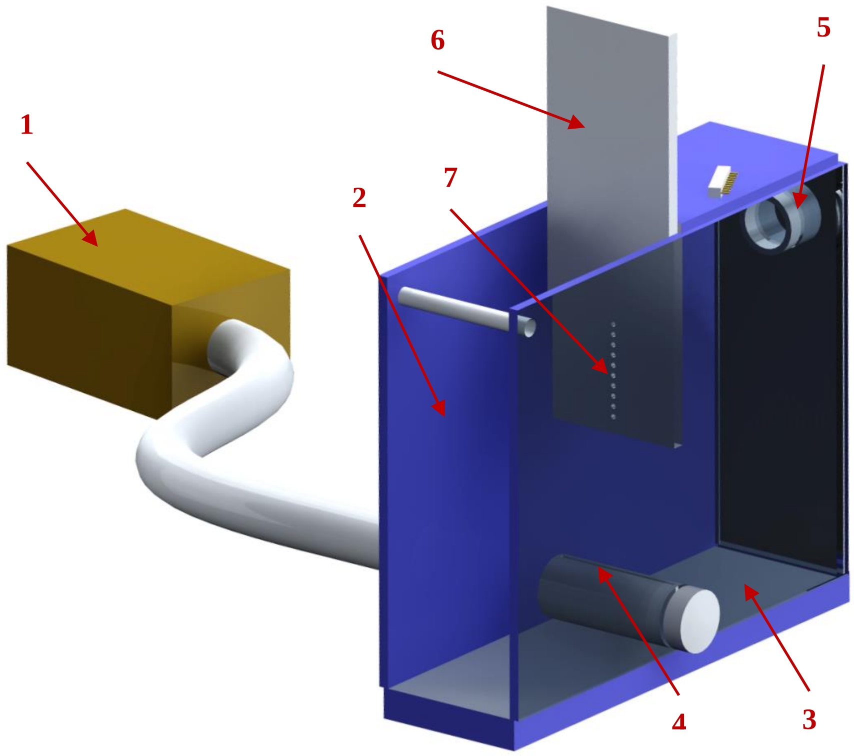


Figure 4. Schematics of the measurement setup. 1 – blower, 2 – outdoor space, 3 – indoor space, 4 – jet outlet, 5 – inlet orifice, 6 – gate, 7 – wall pressure taps on the gate.
Figure created by Judit Bogár.

# Measurement tasks

## General tasks

Depending on the assignment, a leaking or non-leaking air curtain is to be constructed.

In case of each task, the $p_k$ ambient pressure, the $T_k$ ambient temperature and the geometry is to be measured. The first two are to be recorded both before and after the measurements, then the density of the air can be calculated from their averages.

Then a parameter range is to be investigated, while measuring the following quantities, depending on the measurement task:

- $\Delta p_d$ dynamic pressure of the air curtain jet
- $b$ doorway size
- $\beta$ jet angle
- $\Delta p$ difference between the inner and outer (ambient) pressure

The $\Delta p_d$ jet dynamic pressure has to be measured at 4-5 points along the jet and these values are to be averaged to reduce the effect of non-uniform outflow.

In each setting, the 10 pressure outlets above the doorway are to be measured, too. From this data, we can determine whether and how the air jet reattaches. If the air curtain reattaches in that region, a significantly high pressure is expected at one or more pressure points, due to the dynamic pressure of the impinging jet. If there is no such point, one of the following cases can be true:

a) the air curtain is not able to close, in which case the pressure difference between the inside and the atmosphere is negligible, or
b) the air curtain closes, but it happens above the measurement points, in which case a large depression is expected.

Depending on the 10 wall pressures and the pressure difference between the inside and the outside, determine which is the case! Give reasons for the shape of the pressure distribution with fluid mechanical reasons. Possible reasons are: separation at the sharp inlet edge, flow parallel to the wall, reattachment of the jet, etc.

If the speed of the blower is adjusted, the dynamic pressure of the jet needs to be recorded at each setting.

The used digital manometer has to be calibrated either before or after the measurement.

After the measurement task is completed, the behaviour of the air curtain can be visualized. By injecting oil fog into the blower suction pipe and using a laser sheet, the streamlines can be inspected. Compare the experiences with the assumed operating state of the air curtain! Report your experiences in writing and in a graphical form, too (sketches or photos)!

## Task A: non-leaking air curtain

Create a non-leaking air curtain by closing the suction pipe and the various outlets!

Set four different $b$ values, and 5-10 $\beta$ values for each case. Measure the $\Delta p$ depression at each setting, while keeping the blower speed constant! Record the pressure distribution on the gate wall at the extremum points. Evaluate the measurement results by comparing the theoretical and the measured $\widetilde{K}$ values!

## Task B: non-leaking air curtain

Create a non-leaking air curtain by closing the suction pipe and the various outlets!

Keep the gate width constant, and set the gate angle to 5-10 different values. Measure the pressure difference and the wall pressure distribution! Repeat the measurements with the same parameters, but at a different blower speed! Compare the $\widetilde{K}$ values for the two cases!

### Task C: leaking air curtain

Open the inlet orifice and create an outwards-leaking air curtain!

Set different operating states by changing $\beta$ in 5-10 steps at two different $b$ gate widths. Measure the $\Delta p$ depression, and the $\Delta p_{mp}$ pressure drop on the inlet orifice on the suction pipe! Determine the wall pressure distribution at the extremum points! Calculate the leakage flow rate $q_l$ ! Repeat the measurements with the same parameters with the orifice closed! Compare the leaking and non-leaking cases!

# Evaluation

Summarize the set and measured values in a tabular form. Show the pressure differences, the dynamic pressure of the free jet and the leakage flow rate as series of lines in a 2D diagram. Assuming there is no leakage flow, calculate the pressure difference from the equations given above and compare them to the measurement results.

Calculate the following dimensionless parameters: $B, \sin\beta, D$. If there was leakage, calculate $Q = q_l/q_j$, the ratio of leakage flow rate and jet flow rate. $q_l$ leakage flow rate can be measured using the orifice on the suction pipe. Show the connection between $D$ and $Q$ in a diagram!

Calculate the $K$ coefficient from the measured data and compare it to the $\widetilde{K}$ function available in literature.

Describe the behaviour of the system: is there a qualitative or quantitative agreement between measured and calculated values? In which range of parameters is the agreement acceptable? Is there a range of parameters where the behaviour differs significantly from the theoretical one? How can we describe the system there? What formula can be found there to connect the input and output parameters? Write an evaluation based on physical conclusions and your previous studies!

Using the calibration, comment on the reliability of the digital manometer. If the errors are large, use the calibration formula to correct the results!

# Assessment of measurement uncertainty

In the report, the values of the parameter $K$ have to be presented together with their error bars. For the uncertainty calculation, the following values can be used. Uncertainty of the digital manometer: 2 Pa [5]. The uncertainties of other measured quantities are to be judged based on the devices applied to measure them!

# References

Air curtains and their operation [1], momentum theorem [2], planar free jets [3]. Measurement devices, processes [4].

[1] Lajos Tamás: Az áramlástan alapjai, Budapest, 2008. Chapter 7.6 (in Hungarian)

[2] Lajos Tamás: Az áramlástan alapjai, Budapest, 2008. Chapter 7.1.1 (in Hungarian)

[3] Lajos Tamás: Az áramlástan alapjai, Budapest, 2008. Chapter 7.5.2 (in Hungarian)

[4] Lajos Tamás: Az áramlástan alapjai, Budapest, 2008. Chapters 6.2.5, 6.3.1-5 (in Hungarian)

[5] EMB-001 “kézi digitális nyomásmérő berendezés” user manual http://www.ara.bme.hu/oktatas/tantargy/NEPTUN/BMEGEATAG11/MAGYAR_kepzes/2015-2016-II/lab/Digitalis_manometer_EMB-001_Manual.pdf