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THE INFLUENCE OF AIR OUTLET DIRECTION ON THE STABILITY OF AIR FLOW PATTERNS IN LARGE HALLS

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SUMMARY

In room air flow problems especially in large halls with jet air ventilation the Archimedes Number Ar is known as the most important parameter. Ar is kept constant for scale model tests but one generally did not pay attention to physical meaning of Ar-components.

An extended Ar-definition is proposed, and based on this parameter

$$Ar^{*} = \sin\alpha \pm \frac{2gH\Delta\vartheta}{T \cdot w^{2}}$$

α = air outlet angle against horizontal direction

one can better judge non isothermal air flow patterns in a room.

We get now different interpretation for vertical and general flow direction, and it has been proved that Ar can help in design and control to reach a good air flow quality.

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1. INTRODUCTION

In the last 30 years the air flow in rooms, especially in large halls, has become an important field of research work.

In this context the main parameters have been clarified. We know that besides Reynolds - Number Re the Archimedes Number Ar gives the essential information on general air flow characteristics - and under certain turbulence conditions ($Re > 3 \cdot 10^4$) Ar is the main parameter.

Since the basic work of Müllejans [1] several authors have used this method of flow description to solve air flow simulation problems [2, 4, 6, 7] - mainly in experiments with scale - models where tests were executed under fixed Ar-Numbers [3].

But soon one found out, that results which gave principally correct flow information in different scale models, were not completely clear [5]. One always finds differences in flow stability that may be explained by additional parameters.

Nevertheless, it is very helpful to use Ar especially for jet air distribution systems. Though general theory is now rather precise [8], we have started practical design and control work in using Ar-numbers.

But if we go into detail we find very different basic definitions according to specific length, and numerical values of Ar are consequently different, so that physical interpretations due to numerical values are not possible.

Therefore we propose to modify and clarify Ar-definition without changing fundamental meaning.

This brings the possibility to better analyze influence of air intake direction in the cooling and heating case.
If we physically understand the meaning of Ar, we can use it more in better engineering application. There exist already some applications that will be explained in the following, where we are concentrating on jet air flow.

2. GENERALIZED ARCHIMEDES NUMBER Ar*

2.1 Conventional Ar-Definitions

Ar is the relation of buoyancy forces to impulsional forces in the air movement in a room.
This dimensionless number dominates if turbulence is high, if Reynolds Number is high and if we limit our observation to the general air flow structure in a room not too near at the walls.

If we regard at a circular air outlet where the air enters the room with a velocity w_0 and with a temperature difference $\Delta\vartheta$ to room air temperature we find the following situation:

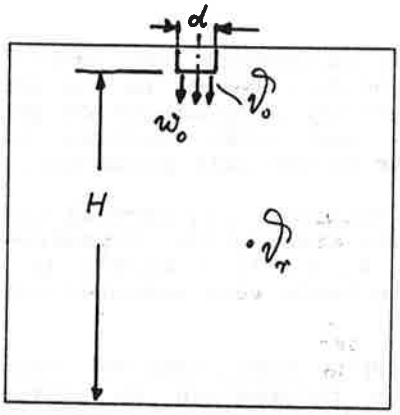

Fig. 1: Parameters for Ar

Resulting pressure values for impulsional and buoyancy forces are

$$p_I = \frac{\rho}{2} w_0^2 \qquad (1)$$

$$p_B = \frac{\rho g H \Delta\vartheta}{T_r} \qquad (2)$$

$$\Delta\vartheta = (\vartheta_r - \vartheta_0)$$

If we regard the classical definition of Ar we get

$$Ar = \frac{p_B}{p_I} = \frac{2 g l \Delta \vartheta}{T_r w_o^2} \qquad (3)$$

with l = characteristic length in the room

In most cases Ar is used in comparison to different scale rooms, and one only wants to keep Ar = const.

Therefore we often neglect the factor 2.

$$Ar_1 = \frac{g \cdot l \cdot \Delta \vartheta}{T_r w_o^2} \qquad (3a)$$

Now we look at the characteristic length in Ar that is after Fig. 1 the effective height H for buoyancy forces.

In many publications this characteristic length is freely chosen e.g. as the outlet diameter (for nozzles) or the slot width (for slot diffusers) [1, 2, 4], what has nothing to do with the actual physical buoyancy effect and brings Ar-values in mind that cannot be interpreted physically.

$$Ar_2 = \frac{g d \Delta \vartheta}{T_r w_o^2} \qquad (3b)$$

We propose generally to use H for Ar-Number.

2.2 A New Approach to Archimedes Number

We know that a constant Ar permits to compare different tests with similar geometry under the same thermal conditions. But what occurs if thermal conditions vary?

In case of cooling we find that buoyancy forces add to impulsional forces, if we introduce the air from the top. In case of heating they subtract.

Fig. 2. compares the essential cases of air introduction.

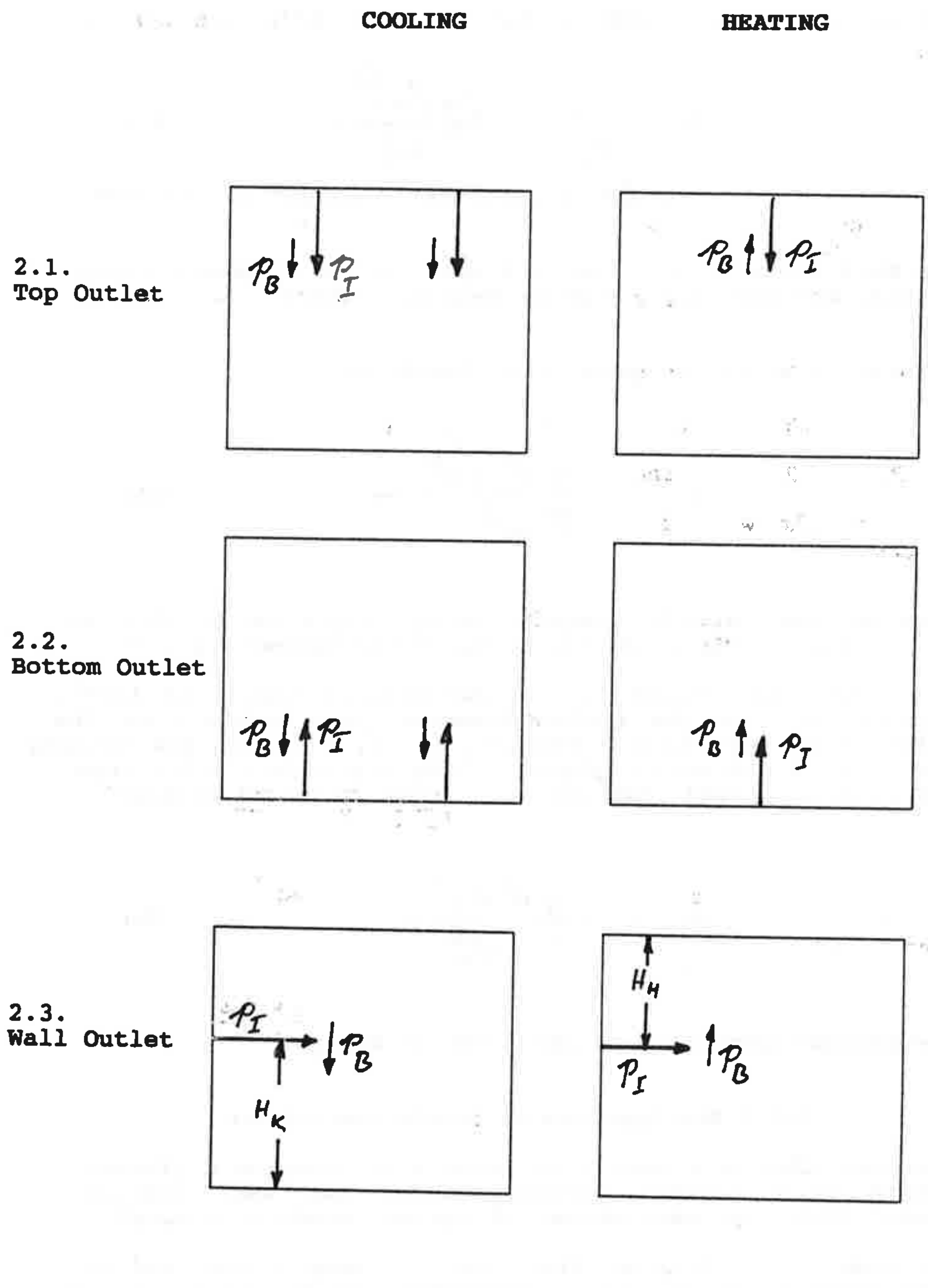

Fig. 2: Direction of buoyancy and impulse effect for different air outlet positions.

In comparing those figures we recognize that the scalar function

$$Ar = \frac{P_B}{P_I}$$

does not directly explain quantitatively what will happen in the room.

In Fig. 2.1. "Cooling" $P_I + P_B$ leads to a resulting vertical flow,

in Fig. 2.1. "Heating" it is $P_I - P_B$,

In Fig. 2.2. "Cooling" it is $P_I - P_B$,

in Fig. 2.2. "Heating" it is $P_I + P_B$,

and for the wall outlet Fig. 2.3. we find as a resulting angle

$$\frac{P_B}{P_I} = \tan \alpha \quad . \qquad (4)$$

If we define a generalized dimensionless number

$$Ar^* = \frac{\text{Resultant vertical force}}{\text{Impulsional force}}$$

we can better judge room air movement from Ar^*.

This leads to

$$Ar = \frac{P_I \pm P_B}{P_I} = 1 \pm \frac{2gH\Delta\vartheta}{T_r w_o^2} \qquad (5)$$

$$= 1 \pm Ar$$

for vertical cases 2.1. and 2.2.,

$$Ar^* = \pm \frac{P_B}{P_I} = \pm Ar \qquad (6)$$

for horizontal air outlet (Fig. 2.3).

Corresponding to Fig. 2.3. we have to pay attention that in the heating case the reference height has to be H_H :

$$Ar^* = \frac{2g H_H (\vartheta_r - \vartheta_o)}{T_r w_o^2} < 0 \qquad (6a)$$

in the cooling case we use H_K:

$$Ar^* = \frac{2g H_K (\vartheta_r - \vartheta_o)}{T_r w_o^2} > 0 \qquad (6b)$$

From eq. (4) we recognize the deviation of air jet against the horizontal direction:

$$\alpha = \text{arc tan } (Ar^*) \qquad (4a)$$

General outlet direction:

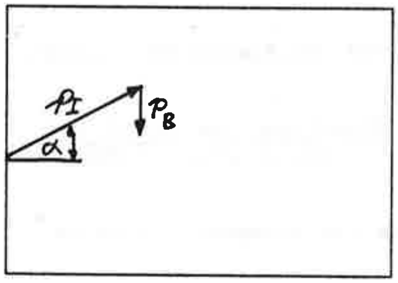

Fig. 3: General combination of Impulse and Buoyancy force

Here we get

$$Ar^* = \frac{p_I \sin\alpha \pm p_B}{p_I} \qquad (7)$$

with

α = angle against horizontal direction

α = 90° means vertical impulse(eq. (5))

α = 0° leads to eq. (6)

So we generalize

$$Ar^* = \sin\alpha \pm \frac{2g H \Delta\vartheta}{T_r w_o^2} \qquad (7a)$$

2.3 Physical Signification and Numerical Values of Ar_V^* and Ar_H^*

What can we learn directly from eq. (7)?
If we want to have a nearly horizontal air flow we may compensate the deviation angle caused by buoyancy forces in changing the air outlet direction so that

$$Ar^* = 0$$

We get

$$p_I \sin \alpha + p_B = 0$$

$$\alpha = \pm \arcsin \frac{p_B}{p_I} \qquad (8)$$

In the heating case α has to be directed downwards, in the cooling case upwards.

This technique has been used already in [3], but variable angles were fixed experimentally.

The generalization of Ar^* permits to use it for variable loads - also in the

Isothermal case:

$Ar^* = 0$ for horizontal flow

$Ar^* = 1$ for vertical flow

General:

$Ar^* > \sin \alpha$, if impulse and buoyancy have the same direction

$Ar^* < \sin \alpha$, if impulse and buoyancy have opposite directions.

Examples:

To become acquainted with the new Ar-Numbers we form some examples:

$$p_B = \frac{\rho g H \Delta\vartheta}{T_r} \quad \text{with} \quad \rho = 1{,}2 \text{ kg/m} ,$$

$$g \cdot \Delta\vartheta = 100 \frac{m}{s^2} \cdot K, \quad \Delta\vartheta \cong 10 \text{ K}, \quad T_r = 300 \text{ K}$$

leads to

H =	3	5	10	15	m
p_B =	1,2	2	4	6	Pa

$p_I = \frac{\rho w_o^2}{2}$:

w_o =	2	3	4	5	6	m/s
p_I =	2,4	5,4	9,6	15	21,6	Pa

From those tables we can now combine different solutions and find out realistic Archimedes-Numbers:

Table 1: Vertical Air flow: $\quad Ar_v^* = 1 \pm \frac{p_B}{p_I}$

Ar_v^*	H = 3 m w = 2 m/s	H = 5 m w = 2 m/s	H = 5 m w = 4 m/s	H = 10 m w = 2 m/s	H = 10 m w = 4 m/s	H = 10 m w = 6 m/s
Cooling from the top	1,5	1,37	1,21	2,67	1,42	1,19
Heating from the top	0,5	0,63	0,79	−0,67	0,58	0,81

General experience is that an air flow should be stable, that means that Ar should be mainly governed by impulsional forces. It should always differ not too much from 1.

So with growing height the velocity also must rise.

H = 5 m and w = 4 m/s may be good, ($Ar_V^* = 1{,}21$)

H = 10 m, w = 6 m/s might also be good. ($Ar_V^* = 1{,}19$)

H = 10 m, w = 2 m/s is very unstable and might bring problems. ($Ar_V^* = 2{,}67$)

We want to point out here that those tendencies are not sufficient to select and dimension a ventilation system. Some additional parameters as specific air volume and special geometrical outlet pattern have to be taken into consideration.

But if we have selected a system and if we have an idea how to realize the outlet situation, the new extended Ar -Number might help us to understand principal flow behaviour.

Table 2: Horizontal flow: $Ar_H^* = \pm\frac{P_B}{P_I} = \pm \tan \alpha_1$

	H = 3 m w = 2 m/s	H = 3 m w = 4 m/s	H = 5 m w = 2 m/s	H = 5 m w = 4 m/s	H = 5 m w = 6 m/s
Ar_H^*	± 0,5	± 0,22	± 0,83	± 0,21	± 0,093
deviation angle	± 26,6°	± 12,5°	± 40°	± 11,8°	± 5,3°

Ar is positive in case of cooling, deviation angle downwards, negative in case of heating.

What air flow direction must be chosen for H = 5 m, w = 2 m/s, to compensate at the beginning the angle deviation?

From eq. (8) we get $\alpha_2 = \arcsin \frac{p_B}{p_I} = 56°$!

The interpretation of horizontal Ar^*_H shows that $|Ar^*_H|$ should not exceed 0,3 what leads to an deviation angle of about 17°.*)

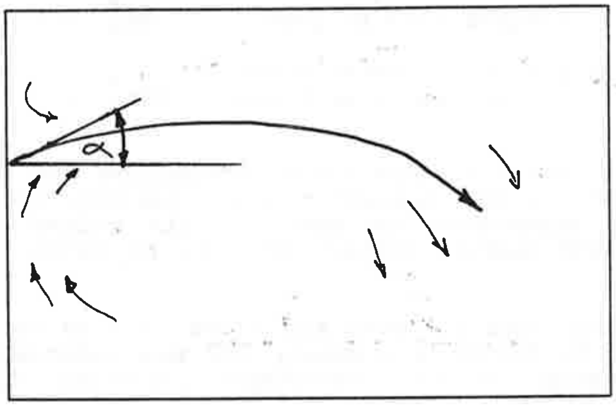

Fig.4: Resulting Horizontal flow with compensated angle deviation

Figure 4 shows the optimization of room air flow. The air jet must remain nearly in a constant height above the occupational zone and penetrate only slowly when impulse and temperature differential are almost negligible.

3. GENERAL FLOW CHARACTERISTICS

Ar^*-interpretation has shown that we get completely different phenomena when selecting an air flow system with vertical or with horizontal flow.

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*) **Note:** We can til now not decide whether the angle of geometric addition of forces is really the angle of resultant velocity vector, but energetically it should. This has to be proved experimentally.

3.1 Vertical flow

If we make a selection with vertical flow we have to choose a pattern for a large hall that brings sufficiently good results (Fig. 5.).

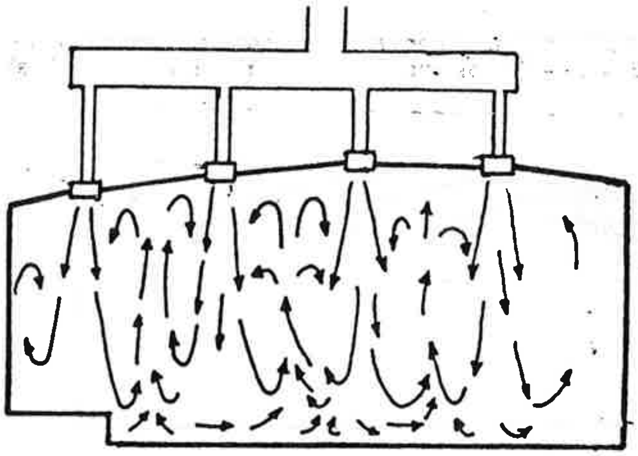

Fig. 5: Air flow pattern for a large hall with vertical air jets.

In this case we are able to guard the flow pattern under different load conditions without changing outlet direction.

Ar^* shows why this is possible. No angle function occurs in eq. (7a) for $\alpha = 90°$ though for all other basic angles buoyancy force changes air jet angle!

If we find an effective control system we are able to guarantee a good functioning of ventilation under all load conditions. This system has been found as a combination of velocity- and temperature control in the cooling case leaving Ar = const (see 4.).

Only in changing the impulse function we reach principally similar air flow pattern also in the heating case.

3.2 Horizontal and General Flow

Here the situation is completely different. Also in this case we may try to keep Ar = const. under different load conditions. But this does not mean to reach the same flow pattern here.

A reduction of buoyancy force cannot be compensated by a reduction of impulsional force. If Ar = const. only the resultant deviation angle will be the same, but the jet penetration depth into the room will change (Fig. 6):

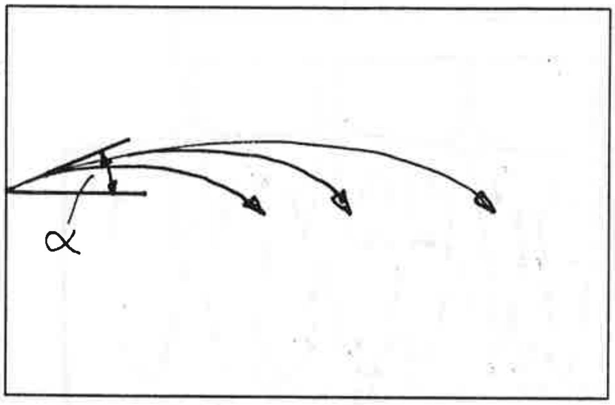

Fig. 6: Different air flow patterns with constant Ar^* or deviation angle α .

Only a further variation of α may give a possibility to reach the same width with the outlet system.
But the control philosophy for this procedure is not yet quite clear. Changing of the angle means that penetration angle into the occupational zone will also vary. It seems today that a lot of work must be done to find an optimum with those systems.

4. PRACTICAL EXAMPLE

An Archimedes Control System for ventilation of big halls has been developed and installed in several projects in Germany.

If we have a constant outlet configuration (Fig. 5) we have to adapt with the ventilation system to the variable cooling load as follows:

$$\dot{Q}_o = \text{Maximum Cooling Load}$$

is extracted of the hall with a certain air volume (outlet velocity w_o) and a maximum temperature differential $\Delta\vartheta \cdot w_o$.

If only a load $\dot{Q} < \dot{Q}_o$ exists we can reduce either $\Delta\vartheta$ or w or both.

If $$q = \frac{\dot{Q}}{\dot{Q}_o},$$

then $$q = \frac{\Delta\vartheta}{\Delta\vartheta_o} \cdot \frac{w}{w_o} \quad . \qquad (9)$$

If Ar = const., then $$\frac{\Delta\vartheta}{w^2} = \frac{\Delta\vartheta_o}{w_o^2} = \text{const.} \qquad (10)$$

We put (10) into (9) and get

$$\left(\frac{w}{w_o}\right)^3 = q \quad \text{or} \quad \frac{w}{w_o} = (q)^{1/3} \qquad (11)$$

and consequently $$\frac{\Delta\vartheta}{\Delta\vartheta_o} = (q)^{2/3} \qquad (12)$$

For q = 0,5 we get under these conditions

$$\frac{\Delta\vartheta}{\Delta\vartheta_o} = 0{,}63 \quad \text{and} \quad \frac{w}{w_o} = 0{,}79$$

Practically we are measuring temperature differential room/supply air temperature, and as a fixed function we reduce air volume or velocity dependent on $\Delta\vartheta$.

5. CONCLUSION

In many cases the Archimedes Number Ar is used to realize scale model measurements of air flow in air conditioned rooms. So one is sure under certain border conditions to get in the model tests the same results as in reality.

No definition standard has been formed, and so a physical significance of Ar was in most cases not in mind.

Here we tried to come back to physical roots of Ar-definition. An extended definition permitted to distinguish different cases, and it became clear that horizontal and vertical air flow are quite different phenomena.

The new extended Archimedes Number Ar^* permits to characterize stability as before; in horizontal cases the incident angle deviation may be calculated.

Control theory permits to find good stability of air flow independent of cooling load when Ar = constant can be realized.

We hope that based on some suggestions in this paper we will proceed to a continuously better understanding of air flow in halls.

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