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SELF-AERATED BOUNDED FLOWS IN SPECIAL HYDRAULIC STRUCTURES. PART 1.

A SHORT REVIEW ON DESIGN CONCEPTS AND SIZING PROCEDURES OF AERATORS.

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ABSTRACT

In a number of hydraulic structures, significant fluid-dynamical differences may be observed between flows which are well aerated and flows which are not ([16]). These differences are not just a matter of scientific speculation. Effective or ineffective aeration may be in fact responsible for inducing a variety of flow regime transitions, some of which may result desirable in particular situations and undesirable in other cases ([16]). When flows are bounded the venting system actually rules the behaviour of the entire system. Despite the importance of aeration for the performance of many hydraulic structures, design methods and procedures, in force of the great complexity of the involved physical phenomena, may be still nowadays quite simplified and experimental tests on large scale physical models are to be considered unavoidable to properly size the air supply system ([15], [21]).

In the first part of the paper, structural layout and flow patterns which may be observed in bottom outlets, chute spillways, baffled weirs and leaping weirs are described. Flow regime transitions occurring in these structures are shown to be ruled to a great extent from the sizing of the aerators, giving evidence that such elements are unavoidable whenever civil structures and mechanical equipment are prone to cavitation risk. Stemming from these premises, in the second part of the paper it is stressed that common design procedures of air vents are based upon the hypothesis that the flow of air through vents may be treated as that of an incompressible fluid. It is brought to light however that this procedure contrasts, not so infrequently, with many experimental results collected from various researchers over more than 50 years ([6], [15], [22]). A compressible flow formulation is therefore reckoned to be necessary to predict the main flow characteristics of air through ducts of variable size, length and roughness.

NOMENCLATURE

The following list of symbols is common to Part 1 and Part 2 of “Self-aerated bounded flows in special hydraulic structures”. The two complementary parts are presented at HEFAT 2008.

Roman symbols: upper-case letters

A	$[m^2]$	Area of the pipe
B	$[Nm^{-2}]$	Bulk modulus of compressibility
D	[m]	Diameter of the pipe
E	$[Jkg^{-1}]$	Total energy per unit mass
H	$[Jkg^{-1}]$	Enthalpy per unit mass
K	$[Jkg^{-1}]$	Kinetic energy per unit mass
L	[m]	Length
M	[kg]	Mass or total mass flow
$\dot{M}$	$[kgs^{-1}]$	Mass flow per unit time
Q	$[Jkg^{-1}]$	Heat transfer per unit mass
$\dot{Q}$	$[Jkg^{-1}s^{-1}]$	Heat transfer per unit mass per unit time
R	$[Jkg^{-1}K^{-1}]$	Engineering gas constant
S	$[Jkg^{-1}K^{-1}]$	Entropy per unit mass
T	[K]	Absolute temperature
U	$[Jkg^{-1}]$	Thermal energy per unit mass
V	$[ms^{-1}]$	Velocity
W	[m]	Thickness of the pipe wall
Y	$[Nm^{-2}]$	Elastic modulus of the pipe (Young’s modulus)

Roman symbols: lower-case letters

c	$[ms^{-1}]$	Speed of pressure waves
g	$[ms^{-2}]$	Gravitational acceleration
k	[−]	Adiabatic index

n	$[-]$	Polytropic index
$\dot{q}$	$[Jm^{-1}s^{-1}]$	Heat transfer per unit length per unit time
r	[m]	Radius
t	[s]	Time coordinate
x	[m]	Cartesian x-axis coordinate
y	[m]	Cartesian y-axis coordinate
z	[m]	Cartesian z-axis coordinate

Greek symbols: upper-case letters

W	$[m^3]$	Volume or total volume flow
$\dot{W}$	$[m^3s^{-1}]$	Volume flow per unit time

Greek symbols: lower-case letters

a	$[-]$	Function
b	$[-]$	Function
g	$[-]$	Function
e	$[-]$	Function
q	$[-]$	Angle of inclination of the pipe/vent
m	$[Nsm^{-2}]$	Dynamic viscosity
n	$[m^2s^{-1}]$	Kinematic viscosity
p	$[Nm^{-2}]$	Absolute pressure
r	$[kgm^{-3}]$	Density i.e. mass per unit volume
s	$[Nm^{-1}]$	Interfacial tension
y	$[-]$	Volumetric fraction

Super-scripts

Sub-scripts

∞	Infinity
B	Bubble
G	Gas
J	Jump
L	Liquid
M	Mixture
R	Reservoir
V	Vapour
W	Water
OT	Outlet Tunnel
MPC	Main Pipe/Channel
LPC	Lower Pipe/Channel
UPC	Upper Pipe/Channel

INTRODUCTION

In many engineering applications free surface flows are usually investigated ignoring the interactions between water and air, implicitly assuming that shear stresses at the water-air interface are negligible. If this simplifying hypothesis may be accepted in classical problems of hydraulics, it is indeed misleading in all cases in which, due to the presence of high velocity flows, shear stresses developing at the interfaces contribute to momentum diffusion between water and air as well as to viscous dissipation, at times also resulting in mass transfer from one phase to the other. When shear stresses between water and air become important, single-phase incompressible flow equations fail to predict reality and multi-phase compressible flow equations are therefore needed to make the fluid-dynamic problem well posed both mathematically and physically.

In the more general theory of two-phase flows there is no real need to specify a priori which of the two fluids is moving faster. However in most hydraulic structures it is the water flowing at high speed which induces the surrounding air to move by drag and entrainment thus giving reason of why two-phase flows in these specific applications are usually referred to as self-aerated flows. Self-aerated flows furthermore may occur either in open channels or closed conduits. The distinction is once more not trivial because in the first case the air flow induced from the water motion does not affect significantly the pressure distribution in the structure while in the second case not only the pressure distribution may change but the extent of this variation is strictly regulated from the design of the venting system, which may also be responsible for inducing or not transitions between different flow regimes ([4], [5]). To further clarify some points which may be considered obscure or enigmatic by a part of the readers, let us analyse more in detail the behaviour of some hydraulic structures in which self-aerated flows develop in a bounded environment and for which the venting system is a rather important design parameter. Typical hydraulic structures of this type requiring a two-phase flow approach in their design and testing are morning glory spillways and vertical shafts ([4]), bottom outlets ([11], [17]) and chute spillways ([8], [13]) and, to a lesser extent, flow diverters such as baffled weirs and leaping weirs ([1], [10]).

Bottom outlets, for instance, are to be considered crucial components of dams. Their role is essential in controlling both the filling and emptying of the reservoirs for either safety or rehabilitation reasons, in removing sediments, in releasing water for irrigation purposes and in preventing flood risks by diverting excess flow rates ([2], [12], [18]). From a structural point of view, bottom outlets, as it is sketched in Figure 1, are essentially made up of a tunnel connecting the reservoir upstream to the river downstream of the dam. From an hydraulic point of view, instead, sluice gates, placed in the gate chamber, divide the tailrace tunnel into an upstream part (which may also be very short) always working under pressure and a downstream part in which, as rather simplified situations, either free surface or pressurised flow may occur ([11], [18]). Downstream of the gates, a connection with atmosphere is to be provided, at least for high dams and long tunnels. In the downstream portion of the tunnel, in fact, the flow velocity can reach extremely high values, because the enormous potential energy accumulated in the reservoir evolves mostly in kinetic energy. High water flow velocities mean high shear stresses at the water-air interface, and thus air is dragged by and entrained into the current and carried away according to the flow transport capacity. Due to these phenomena, the absolute pressure downstream of the gate decreases below the atmospheric value, greatly enhancing the risk for cavitation and cavitation damage and yielding in turn negative pressure gradients along the air flow direction in the venting system and positive pressure gradients along the air-water flow direction in the outlet tunnel. As a result, the above-mentioned pressure gradients induce the air to move from the atmosphere so as to replace that which has been carried away by drag and entrainment ([7], [9]). It is to be carefully noted that observed water-air mixture depths are significantly higher than those expected in well aerated free surface flows, due to both air entrainment which modifies the bulking characteristics of the flow and positive pressure gradients developing along the flow in the tunnel ([11], [17]). For these reasons, pressurisation of the tunnel happens for discharges lower than its maximum hydraulic capacity with well aerated conditions. As it is well known, this effect strictly depends on the actual behaviour of the venting system, which is to be taken into account to perform an accurate analysis.

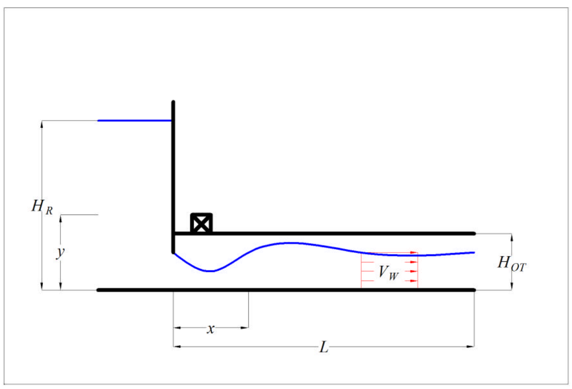

Figure 1. Sketch of the optimum design flow configuration in a bottom outlet. Lengths are not to scale. Black solid lines evidence the structure layout while blue solid lines outline the flow profile. The squared St. Andrew's cross indicates the air supply system.

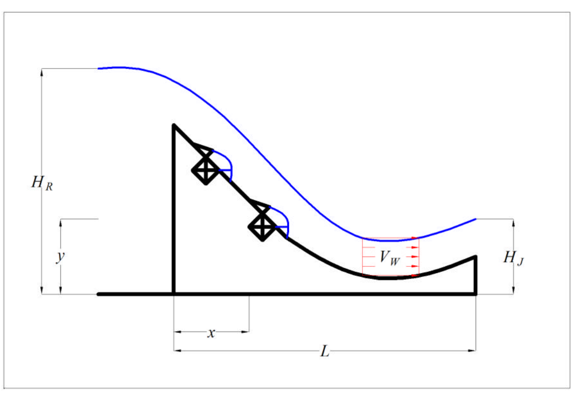

Figure 2. Sketch of the optimum design flow configuration in a chute spillway. Lengths are not to scale. Black solid lines evidence the structure layout while blue solid lines outline the flow profile. The squared St. Andrew's cross indicate the bottom aerators.

Chute spillways, a sketch of which is reported in Figure 2, are also very common hydraulic structures in flood risk prevention and control but, with respect to the main flow features outlined for bottom outlets, they do present substantial distinctions and some analogies. Flow velocities are still very high so that, due to the large interfacial shear stresses, considerable quantities of air are entrained into the flow. In this case however the channel is directly connected to the atmosphere and the pressure on the top interface may be considered always constant. Effects of this phenomenon are contrasting. On the one side in fact large air concentrations result in undesirable larger depths and higher freeboards on the chutes while on the other side reduce significantly the speed of pressure waves in the water-air mixture so that the risk for cavitation damage is greatly decreased ([8], [13], [19]). The air concentration nevertheless is not evenly distributed in the flow cross-section and so it may be necessary to aerate also the bottom part of the flow. When this is the case air ducts have to be designed and constructed following considerations and procedures much similar to those outlined for bottom outlets.

Similar considerations apply also to baffled weirs and leaping weirs ([1], [10]). They are used as flow regulators either in separate or combined networks. From a structural point of view, baffled weirs and leaping weirs, as it is sketched in Figure 3 and in Figure 4, are essentially made up of a blade or an orifice separating the upstream main pipe/channel (i.e. the sewer collector) into a lower pipe/channel (i.e. the sewer diverter) connected to the downstream network or to a storage/treatment plant and an upper pipe/channel (i.e. the sewer emissary) connected to receiving waters. A sluice gate may create an additional flow constriction to limit the flow discharges in the diverter. From an hydraulic point of view, instead, the blade or the orifice are designed so as to intercept entirely peak dry-weather flows plus a definite amount of wet-weather flows. Wet-weather flows exceeding the above-mentioned limit are supposed to overflow the structure and discharge to surface waters. The flow discharge at which the emissary starts working is to be determined according to either hydraulic or environmental reasons. What usually happens, is that during the initial and final parts of rain storms, flow discharges are associated to fluid depths which do not interact with the hydraulic structure, and are therefore entirely intercepted, while, during the central part of rain events, with increasing flow discharges and fluid depths, most of them are conveyed to receiving surface waters. When the latter situation occurs, the sluice gate or the orifice subdivide the collector into an upstream part in which free surface flow is maintained and a downstream part in which either free surface or pressurised flow may occur. In both structures however the design of the aeration duct rules the hydraulic behaviour of the entire hydraulic system, since pressures downstream of the air duct depend on its length, on its hydraulic diameter and on its hydraulic roughness.

From these considerations, two limit situations emerge as common to self-aerated flows in bounded domains. If the ventilation duct is assumed to be properly designed (i.e. the air duct is short and characterised by a large hydraulic diameter and a small roughness), so that the pressure along the air duct and the channel may be considered equal to the atmospheric pressure for any flow condition, well aerated free surface flows may develop as long as the discharges from the control section induce uniform flow depths smaller than the height of the channel or, alternatively, the channel is so short that uniform flow depths cannot develop. Instead, if the ventilation system does not exist or is improperly designed (i.e. the air duct is long and characterised by a small hydraulic diameter and a large roughness), the pressure downstream of the air vent decreases because of the air dragged by and entrained into the current, finally causing the flow attachment to the structure. Pressurised flows result, strictly depending on the downstream conditions at the end of the tunnel. High velocities and low absolute pressures may induce serious problems of cavitations and are to be strictly avoided. Real situations present intermediate flow features between these two limit cases. Care should be taken in all cases to prevent submergence of the air duct. Obstruction of the vent would in fact impede any aeration of the flow at all, even if the vent itself should reveal properly designed in size.

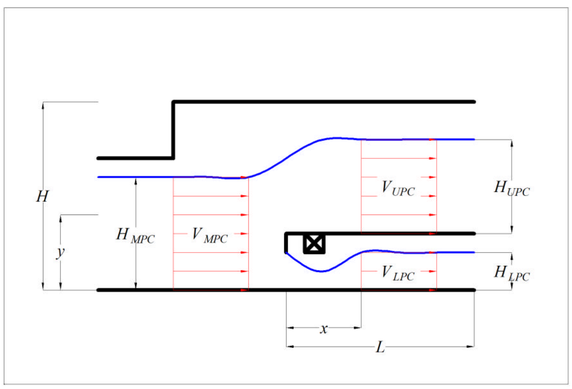

Figure 3. Sketch of the optimum design flow configuration in a baffled weir. Lengths are not to scale. Black solid lines evidence the structure layout while blue solid lines outline the flow profile. The squared St. Andrew's cross indicates the air supply system.

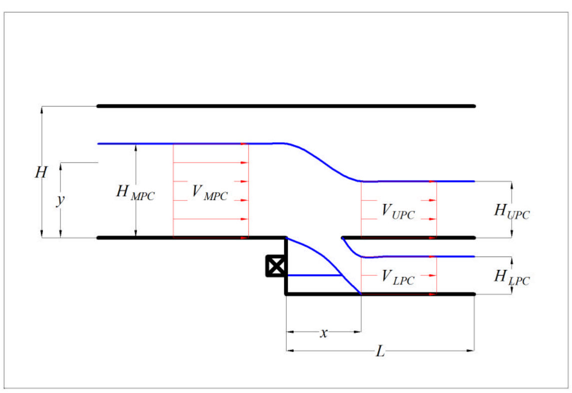

Figure 4. Sketch of the optimum design flow configuration in a leaping weir. Lengths are not to scale. Black solid lines evidence the structure layout while blue solid lines outline the flow profile. The squared St. Andrew's cross indicates the bottom aerator.

BASIC CONCEPTS OF CAVITATION

Cavitation is the process by which a phase transition occurs from the liquid state to the gas state of a substance by reducing the fluid pressure. Though this process is commonly associated to structural damage, cavitation itself does not imply any rupture of material unless it occurs nearby solid boundaries ([5]). Furthermore the incipit of the process always requires the presence of microscopic air bubbles and impurities. When the pressure in an impure liquid is decreased towards its vapour pressure, the radii r_B of microscopic spherical bubbles start to increase. In Figure 5 the equilibrium conditions of microscopic bubbles are illustrated in terms of the ambient pressure p_∞ ([5] and [14]):

$$p_\infty = p_V + p - 2\frac{s}{r_B} \qquad (1)$$

where p_V indicates the vapour pressure of the liquid, s the interfacial tension and p the gas pressure inside the bubble defined through the ideal gas law:

$$\frac{p}{rT} = R \qquad (2)$$

with r, T and R being the gas density, the absolute temperature and the engineering gas constant respectively.

It is to be stressed that when the gas content of the bubbles is very small a critical point may be reached (i.e. the minimum point in the curves of Figure 5). When this situation occurs, any increase in the ambient pressure would yield an explosive growth of the bubble (i.e. vaporous cavitation). Large gas content would instead induce more regular bubble growth (i.e. gaseous cavitation).

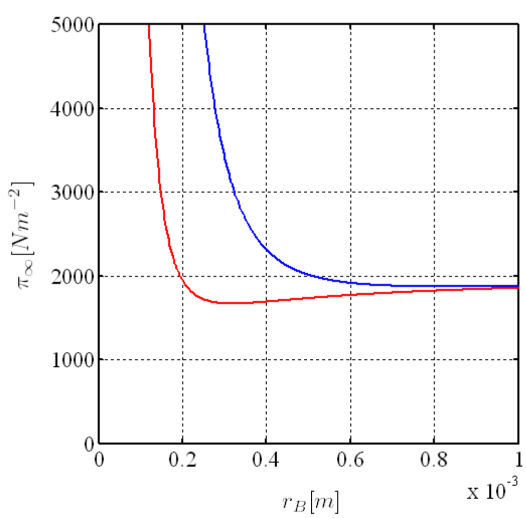

Figure 5. Equilibrium pressure (on the y-axis) versus bubble radius (on the x-axis). The solid blue line illustrates the behaviour of a bubble with a large gas content while the solid red line the behaviour of a bubble with a small gas content.

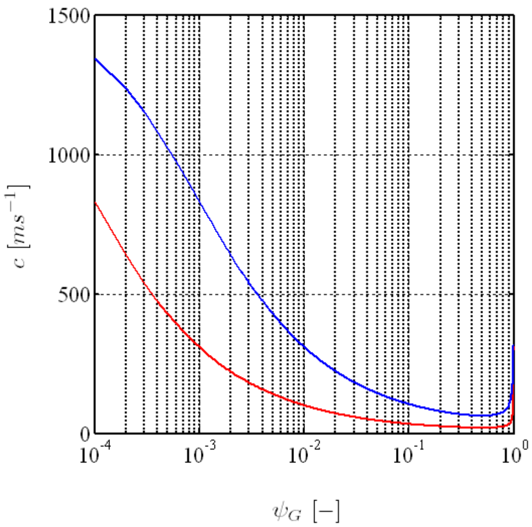

Figure 6. Speed of pressure waves (on the y-axis) versus air volumetric fraction (on the x-axis) in water-air mixtures. Isothermal processes at standard temperature are considered. The influence of ambient pressure is also shown by different colour solid lines. Ambient pressures: 10 atm (blue curve) and 1 atm (red curve).

During the explosive growth of the bubble, pressure waves of enormous intensity propagate in the medium at sonic speed. These pressure waves, when colliding with solid boundaries, are therefore responsible for the structural damage observed on civil and mechanical equipment. It is also evident that the sonic speed of pressure waves in the medium has a major effect on the pressure intensity which can stress the materials.

The speed of pressure waves in a pipe can be shown to be defined in terms of the fluid properties and pipe characteristics as:

$$c = \frac{\sqrt{\dfrac{B}{r}}}{\sqrt{1+\dfrac{B}{Y}\dfrac{D}{W}}} \tag{3}$$

where B is bulk modulus of compressibility for the fluid, Y is the elastic modulus of the pipe while D and W are the pipe diameter and wall thickness ([20]). The previous formulation also holds for mixtures by taking the average mixture properties:

$$r_M = \sum_i r_i \frac{W_i}{W_M} = \sum_i r_i y_i = r_L y_L + r_G y_G \tag{4}$$

$$B_M = \frac{1}{\sum_i \dfrac{1}{B_i}\dfrac{W_i}{W_M}} = \frac{1}{\sum_i \dfrac{y_i}{B_i}} = \frac{1}{\dfrac{y_L}{B_L}+\dfrac{y_G}{B_G}} \tag{5}$$

with:

$$\sum_i \frac{W_i}{W_M} = \sum_i y_i = y_L + y_G = 1 \tag{6}$$

where W denotes the volume occupied by different phases and y the corresponding volumetric fraction ([5], [20]). As it may deduced from Figure 6, in which the speed of pressure waves is plotted versus the gas content of a water-air mixture, even a small gas quantity dispersed in the liquid medium results in consistent attenuation of the sonic speed ([3], [5], [19], [20]) and consequently of the pressure intensities experienced by the boundaries where cavitation occurs. This gives reason of the need for aerating water currents at all locations where low pressures and high velocities result in a significant risk for cavitation.

INCOMPRESSIBLE FLOW EQUATIONS

Given these premises and stated the well-known importance of the air supply system as a design parameter in special hydraulic structures, it is still to be stressed that common procedures in design and testing phases assume the flow of air through air ducts to be incompressible up to sub-pressures of 10'000-15'000 Nm^{-2} (1.0-1.5 m of water column) and velocities of 50-100 ms^{-1} ([4], [5], [18]). This implies that velocities and mass flow rates of air flowing through a nozzle satisfy the following relationships:

$$\frac{V}{\max V} = \frac{\dot{M}}{\max \dot{M}} = \frac{1}{\dfrac{A}{\min A}} = \left(\frac{e}{\max e}\right)^{\frac{1}{2}} \tag{7}$$

with:

$$e = 1 - \left(\frac{p}{\max p}\right) \tag{8}$$

where effects of gravity, singular and distributed energy losses due to friction have been neglected. When two quantities are known within the mass flow rate which is required to aerate the flow, the flow velocity, the air duct geometry and the pressure loss, the remaining variable can be computed in a straightforward manner. These results show that for incompressible flow, nozzle flow characteristics are single-valued functions of the pressure drop through the vent. This formulation however does not show some peculiar features of compressible flow such as choking (i.e. decreasing the downstream boundary pressure below a critical value does not affect anymore the air flow), transition from sub-critical to super-critical flow (i.e. transition from sub-sonic to super-sonic flow), heating or cooling of air (freezing of the inlet might preclude the flow) etc. All these phenomena may in fact play a relevant role in the design of aerators and should actually be taken into account. Data collected by various authors ([6], [15], [21], [22]) in different times through extensive measurements carried out on large-scale hydraulic models have in fact evidenced air sub-pressures and velocities several times larger than the above-mentioned limits. Furthermore, scale effects are also expected to worsen the situation on prototypes ([4]). Analysing the flow of air through vents using compressible flow equations seems therefore unavoidable in order to perceive a better understanding of the flow dynamics and in turn improve the design of air supply systems, which in some cases may be constrained to predefined dimensions.

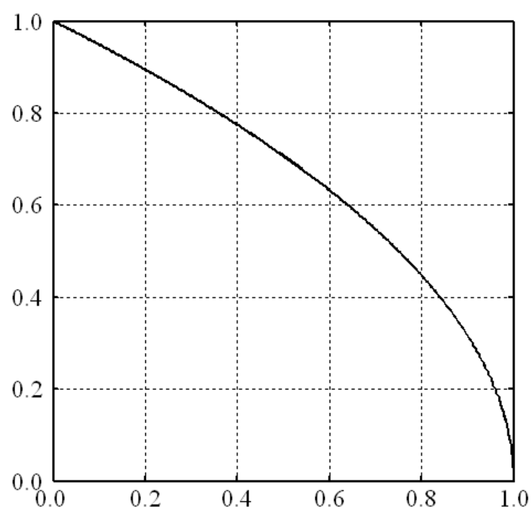

Figure 7. Nozzle flow characteristics (on the y-axis) versus boundary conditions in terms of absolute pressure (on the x-axis). Variables are non-dimensional. Flow area, mass flow rate and velocity coincide for incompressible flow (black solid line).

CONCLUSIONS

This paper has been intended as an introduction to physical characteristics, design problems and solution procedures of some special hydraulic structures in which classical single-phase hydro-dynamical theory fails to predict reality. Structural layout and flow patterns which can be observed in bottom outlets, chute spillways, baffled weirs and leaping weirs have been illustrated, giving evidence that self-aerated flows in bounded environments are ruled to a great extent from the aerator design. Connections between aeration of currents and mitigation of cavitation risk has been substantiated. Common methods adopted in the design of air supply systems treating the flow of air as being incompressible have been also reviewed. The limits of these methods have been discussed showing their contrast with many experimental observations obtained by different authors. The need for modelling the air flow through ducts using compressible flow equations has been therefore recognised as unavoidable in order to design and test the behaviour of air supply systems.

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