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Condensation wave identification in moist air transonic flows through nozzles

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Abstract

This paper identifies the location of water vapour spontaneous condensation during air expansion in convergent-divergent nozzles. The comprehensive analysis proposed herein includes an analytical solution together with experimental and numerical investigations. Numerical calculations are performed using an in-house computational fluid dynamics code based on the solution of Reynolds averaged Navier-Stokes equations supplemented with additional partial differential equations modelling the condensation process of water vapour contained in atmospheric air. Experiments were carried out using an in-house facility adapted for measurements of atmospheric air transonic flows.

Keywords: Air; Transonic flows; Condensation

1 Introduction

Atmospheric air is a mixture of dry air and water in the form of superheated water vapour, dry saturated vapour or dry saturated water vapour with liquid or ice mist. Depending on the combination, three cases can be distinguished. The first one is moist nonsaturated air, the second – moist saturated air and the third – moist oversaturated air. The amount of superheated and saturated water vapour in air is limited. The vapour contained in air starts to condense if the air temperature is lowered isobarically, using cooling installations, to the vapour saturation

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temperature for its partial pressure in moist air (i.e., to the dew point temperature).

Condensation of water vapour contained in atmospheric air is also possible in technological applications without any interference from external heat sources. The drop in the air flow temperature results from air expansion, which may take place in transonic flows, where water vapour condenses, if the speed of sound is exceeded, in very low temperatures (much lower than $0\,^{\circ}$C). Despite low temperatures and due to homogenous (or heterogeneous) condensation, condensed water vapour is in a liquid metastable state (referred to as supercooled water). This state is highly unstable and the supercooled water droplets may transform into ice due to mutual collisions or interaction with walls limiting the flow. The temperature of the onset of spontaneous condensation is much lower than the dew point for stationary (total) parameters.

The theoretical, experimental and numerical analyses presented herein were conducted using convergent-divergent (de Laval) nozzles. The flow through a convergent-divergent (CD) nozzle is one of the fundamental and most common transonic flows. CD nozzles are widely used in technology, especially in transport, power engineering and gas separation processes. Their main purpose is to increase gas velocities to supersonic speed values. Due to very good insulating properties of transonic flows, de Laval nozzles are also used in high-voltage circuit breakers.

Air moisture has an essential impact on many processes taking place in power engineering equipment and machinery. If air cannot be dried at the nozzle inlet in technological applications incorporating convergent-divergent nozzles, it is absolutely necessary to take account of the liquid phase formation, which occurs due to condensation of water vapour contained in atmospheric air.

Analytical works on moist air two-phase flows have been conducted for a long time and the interrelations between parameters on both sides of the condensation wave have helped to understand the phenomena of the heat flux between the liquid and the gaseous phase [1]. For a long time many foreign and Polish researchers have been investigating issues related to the water vapour spontaneous condensation [2,3]. In the field of experimental and numerical studies, the most popular are the works of Schnerr and his research team [4,5,6]. They focus on the analysis of moist air flows through channels such as nozzles, as well as on aerodynamic applications, e.g., on the flow around an aircraft wing profile. Recent works in this field also concern external flows, and they are related to aerodynamic issues [7].

2 Analytical approach

In the case of the moist air diabatic flow with participation of external heat sources, the condensation process of water vapour contained in air starts if the air temperature reaches a value lower than the dew point temperature. The dew point is approximately equal to the water vapour saturation temperature value defined for the water vapour partial pressure. However, if water vapour condensation occurs during air rapid expansion, the process starts when air reaches a supersonic speed value (the Mach number $M = u/c > 1$, where u is the local fluid velocity respect to the boundaries, and c is the speed of sound in the medium), and the air temperature threshold for spontaneous condensation is usually by 30–50 K lower than the dew point temperature calculated for total inlet parameters. This temperature value and the increment in pressure on the condensation wave depend on two factors – relative humidity, Φ_0 , and expansion rate, $\dot{P}$.

Expansion rate $\dot{P}$ expresses the logarithmic rate of the flow static pressure drop, which can be described as follows:

$$\dot{P} = -\frac{d\ln p}{dt} - \frac{1}{p}\frac{dp}{dt} = -\frac{1}{p}\frac{dp}{dx}\frac{dx}{dt} = -\frac{c}{p}\frac{dp}{dx} \approx -\frac{c_0}{p_0}\frac{p_1 - p_2}{l} \ , \tag{1}$$

where c_0 – sound speed at the inlet calculated from pressure p_0 and temperature T_0, p_1 – pressure at the inlet, p_2 – pressure at the outlet; l is a characteristic length, e.g., the length of the nozzle, x – flow direction, t – time, '0' – total parameters.

During moist air expansion, the higher the relative humidity value at the inlet, the higher the air temperature at which condensation occurs and the bigger the increment in pressure on the condensation wave, which means that if relative humidity is bigger, the condensation wave is formed earlier.

Condensation of water vapour contained in moist air due to expansion to supersonic speeds, e.g., in the de Laval nozzle (Fig. 1), is an abrupt (spontaneous) process accompanied by a dramatic change in the flow parameters. The area where the liquid phase is formed in a rapid and spontaneous manner is referred to as the condensation wave and the condensation process unfolds according to the classical theory of nucleation [8] and to the molecular-kinetic droplet growth model [9]. The liquid phase arising on the condensation wave due to spontaneous condensation is in the form of a mist containing a large number of small droplets with the size of a few dozen nanometres. The liquid phase maximum mass content, wetness mass fraction $-y_{max}$, in the moist air mixture depends on the air total temperature and its relative humidity (Fig. 2).

The moist air transonic flow involves the heat transfer phenomenon taking

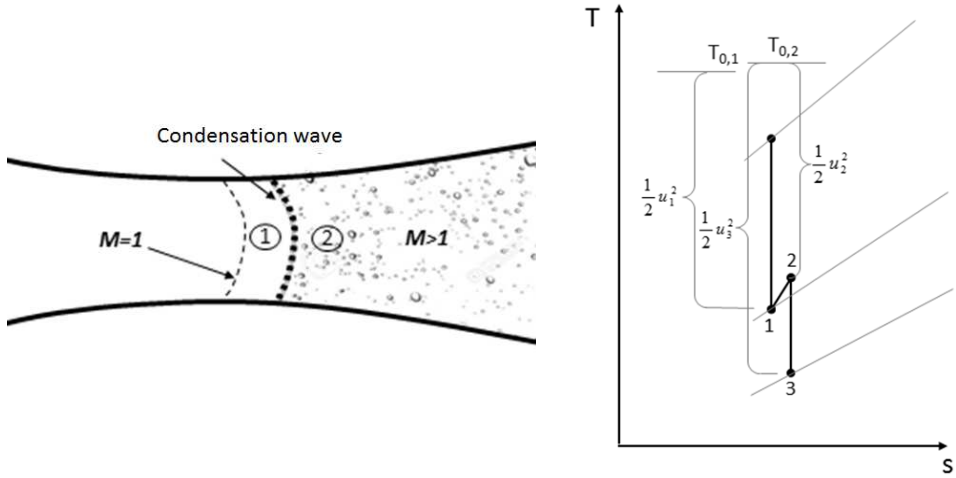

Figure 1: Graphical interpretation of the condensation wave in the nozzle (left) and on the heat chart (right).

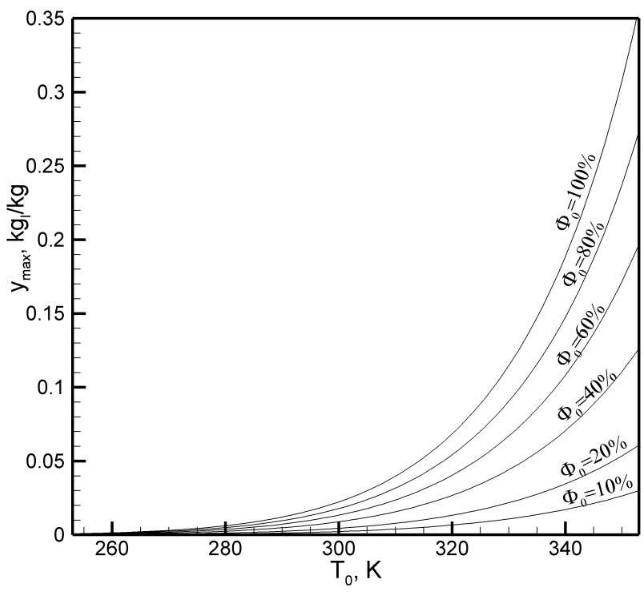

Figure 2: Maximum value of the wetness mass fraction resulting from spontaneous condensation depending on total temperature and relative humidity

place as the water vapour contained in air condenses – the condensation process latent heat is released from the arising liquid phase to the surrounding gaseous phase. The enthalpy of the mixture of air, water vapour and water can be written as follows:

$$h = c_p T - L\, y\;, \tag{2}$$

where T is the static temperature that has an identical value for water vapour, air and the mixture, L denotes latent heat and y is the wetness mass fraction in the air-water mixture, and c_p is the specific heat at constant pressure.

According to the energy conservation law, total enthalpy, h_0, during the water vapour diabatic flow along the streamline has to be constant

$$h_0 = h + \frac{1}{2}u^2 = c_p T + \frac{1}{2}u^2 - yL\,, \tag{3}$$

where u is the flow velocity. It follows that an increase on the condensation wave must occur in total temperature T_0, according to the following relation:

$$T_{0,1} = T_{0,2} - \frac{y_2 L_{0-1}}{c_p} \tag{4}$$

and

$$T_{0,2} - T_{0,1} = \Delta T_0 = \frac{y_2 L_{0-1}}{c_p}\,, \tag{5}$$

where L_{0-1} denotes condensation latent heat. Relation (5) describes the total temperature increment on the condensation wave, which depends on the condensation process latent heat and the liquid phase wetness mass fraction. Assuming that in the process of spontaneous condensation the entirety of water vapour is condensed and transformed into water mist, the dependence of the total temperature increment on the condensation wave on total temperature (usually – ambient temperature in the case of atmospheric air) and on the air relative humidity can easily be presented graphically (Fig. 3). It can be clearly seen that the total temperature increment on the condensation wave rises with total temperature and relative humidity.

3 Experimental and numerical testing

The experimental tests of the moist air transonic flow were carried out using the installation of the minicondensing power plant in the Institute of Power Engineering and Turbomachinery of SUT [10]. In the case of moist air testing, the steam boiler is switched off and the water ejector pump operates continuously

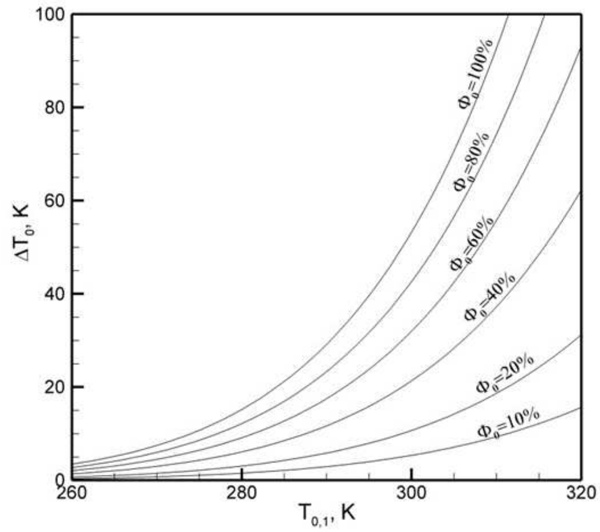

Figure 3: Total temperature increment on the condensation wave depending on total temperature at the inlet and on air relative humidity.

creating vacuum in the measuring channel unit. The total capacity of pipelines and the condenser is about 15 m^3, which, depending on the surface area of the critical cross-section of the testing geometries, makes it possible to perform measurements maintaining constant parameters in the nozzle for a few dozen seconds. Such lengths of time are more than enough to measure static pressure along the nozzle and to visualize the flow field using the Schlieren technique.

The calculations presented herein were made with the use of an in-house academic Computational Fluid Dynamics (CFD) code, which has been developed and used for many engineering applications for over 20 years. This also concerns the computations performed for water vapour and moist air with condensation [11,12]. The applied computational code was used to identify the condensation phenomenon in the transonic flow. In the presented code the Reynolds averaged Navier-Stokes (RANS) equations are solved numerically using the third-order MUSCL (monotomic upstream-centered scheme for conservation laws) type TVD (total variation diminishing) finite-volume scheme with the second-order Runge-Kutta method with time discretization. The k-ω shear stress transport viscous turbulence model is used. The applied model of the compressible, viscous and turbulent flow of moist air is composed of:

- the mass, momentum and energy conservation equations;

- the turbulence model equations;
- the transport equations for the liquid phase arising due to homogeneous condensation;
- the relations modelling the condensation process according to the classical theory of nucleation [8] and to the molecular-kinetic droplet growth model [9,13];
- the equation of state.

Presented flow model assumes that the flow is a no-slip one. In it, the droplet-air relative velocity is omitted, i.e., a droplet moves at the same velocity as air.

During the first stage, experimental tests and numerical computations were carried out for arc nozzles with different diameters of 100, 125, 150 and 175 mm (Fig. 4). The selection of the nozzle geometry was to a great extent dictated by the limitations concerning the making of nozzles intended for experimental testing. In the case of arc nozzles, they were made using own means, on a typical lathe, with no need to apply CNC (computer numeric control) machine tools.

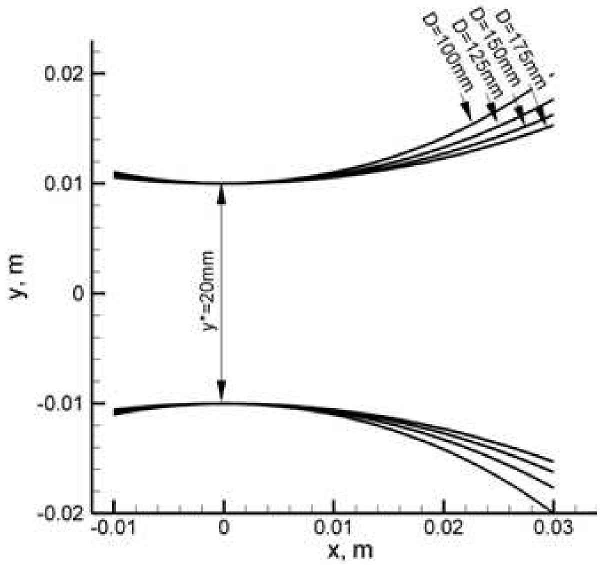

Figure 4: Geometries of convargent-divergent arc nozzles under analysis.

The atmospheric air parameters at the time of experimental testing were as follows: $p_0 = 98.8$ kPa, $T_0 = 297$ K and $\Phi_0 = 43\%$. Identical values were adopted as total parameters at the inlet of the nozzles in numerical computations.

Figure 5 presents the experimental facility during the tests of the convergent-divergent nozzles under consideration and the CFD (computational fluid dynam-

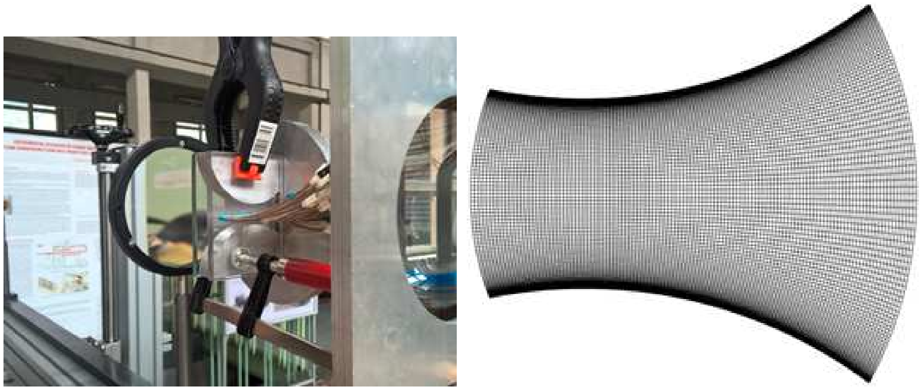

Figure 5: Experimental facility (left) and the nozzle numerical mesh (right).

ics) numerical mesh composed of 121×141×5 nodes. Further increase of the mesh nodes number has no effect on the obtained solution.

It is possible to identify the condensation wave both experimentally and numerically. Testing results are a perfect basis for validation of numerical models. The experimental tests presented herein were performed to measure the static pressure distribution on the side wall along the nozzle centre and to visualize the flow field using the Schlieren technique, which provided the basis for the academic CFD code validation. Figure 6 presents Schlieren images for four nozzles under analysis and a comparison between the static pressure distribution along the nozzle obtained from calculations and measurements. Additionally, the total pressure and the total temperature distributions along the nozzle are shown. A fall in total pressure and a rise in total temperature can be observed on the condensation wave. It can also be seen that the condensation wave is shifted downstream the flow as the nozzle curvature is increased, i.e., as the expansion rate gets smaller. This is confirmed both by the Schlieren image of the experiment and by the static pressure distribution along the nozzle centre.

Figure 7 presents the expansion line and the wetness mass fraction distribution for four nozzles under analysis. It can be seen from the expansion line presented in figure that the calculated increment in entropy on the condensation wave is very close to the value calculated from the entropy definition derived for perfect gas. The wetness mass fraction at the nozzle outlet has an identical value for all the nozzles, differences appear only in the condensation wave area. This confirms previous analytical considerations taking account of the idea that the liquid phase wetness mass fraction arising due to condensation depends on relative humidity and temperature at the nozzle inlet.

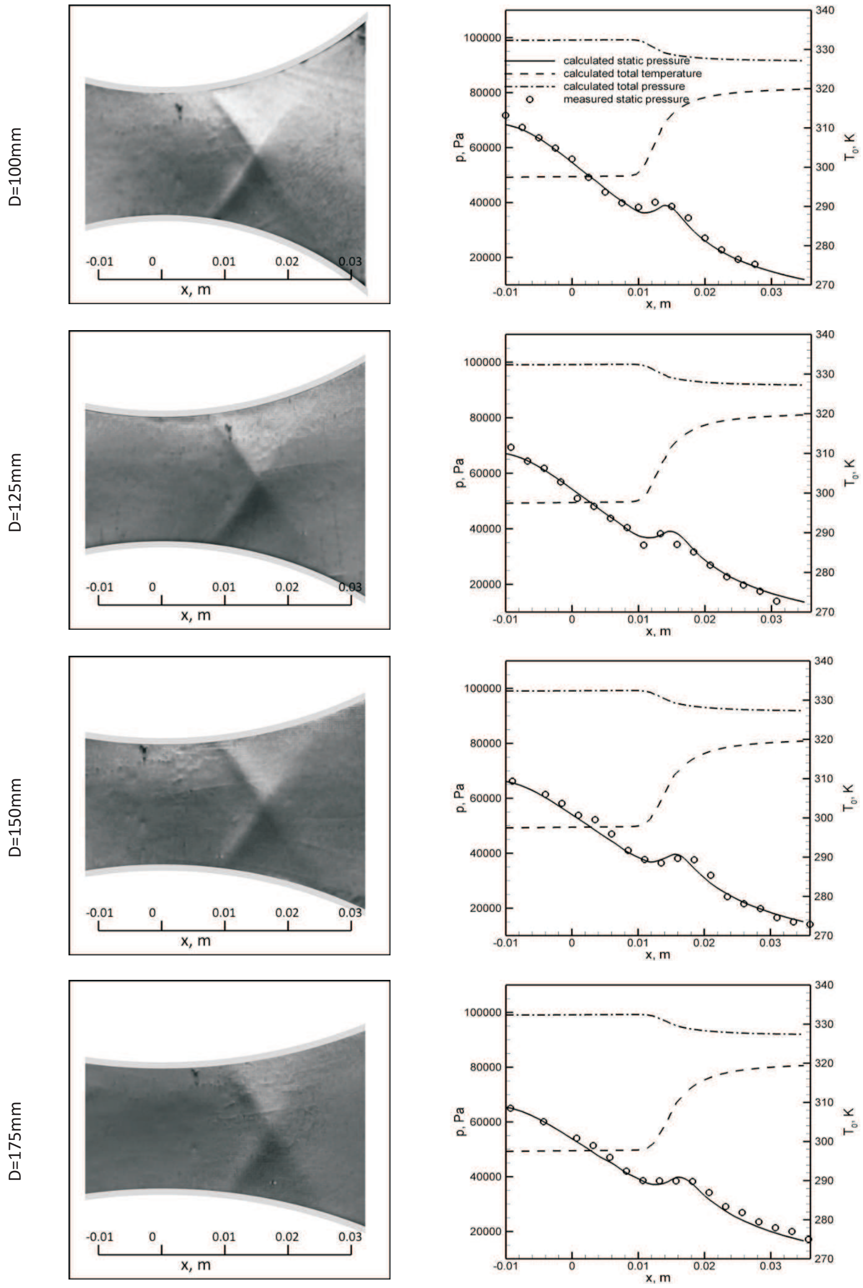

Figure 6: Results for arc nozzles different diameters, D, Schlieren images from the experiment (left) and distribution of pressure, p, and temperature, T_0, along the nozzle centre (right).

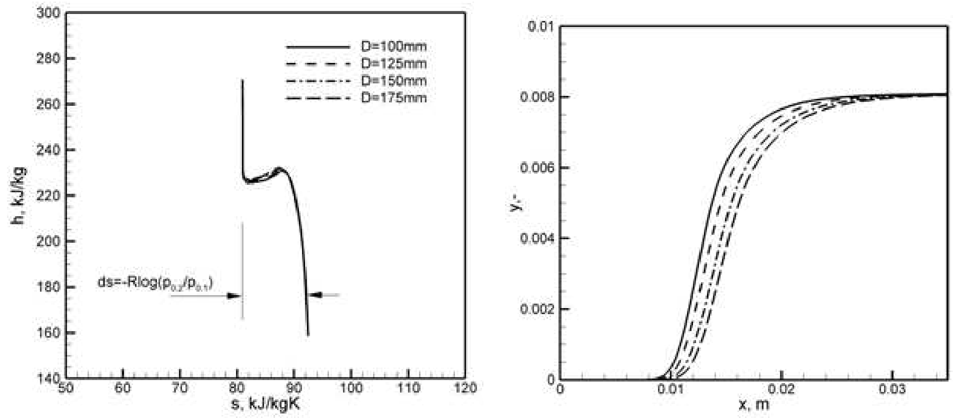

Figure 7: Expansion line (left) and the liquid phase wetness mass fraction distribution (right) along the nozzle centre for 4 analysed nozzles.

4 Summary and conclusions

This paper touches upon the issue of water vapour condensation in the moist air flow through convergent-divergent nozzles. The problem was investigated both theoretically and by means of experimental and numerical testing. The ability of the developed methods to identify the condensation wave during atmospheric air expansion in nozzles was checked. Based on the experiments and numerical calculations, it is concluded that:

- the applied computational model simulates the air flow in convergent-divergent nozzles with water vapour condensation correctly,
- the experimental testing results constitute a good basis for the developed in-house CFD code validation,
- the condensation wave identification based on own experimental and numerical testing corresponds to theoretical analyses concerning changes in total parameters on the condensation wave and the volume of the condensed liquid phase and losses, which proves the good quality of the obtained numerical and experimental testing results.

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