International Journal of Heat and Mass Transfer 114 (2017) 1072–1085

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Comprehensive investigations into thermal and flow phenomena occurring in the atmospheric air two-phase flow through nozzles

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A R T I C L E I N F O

Article history:
Received 19 May 2017
Received in revised form 29 June 2017
Accepted 29 June 2017

Keywords:
Atmospheric air
CFD
Condensation
Convergent-divergent nozzle
Experiment
Transonic flows

A B S T R A C T

Atmospheric air always contains a certain amount of water vapour being an element of the Earth's hydrological cycle. This content, which can be defined by relative humidity for example, has a significant impact on the transonic flow field. What happens then is the water vapour rapid condensation, due to a non-equilibrium process of spontaneous condensation, followed by evaporation of the resulting liquid phase on shock waves arising in a transonic flow. These two phenomena, related to the moist air flow and the heat transfer between the gaseous and the liquid phase on the condensation wave and on the shock wave, are analysed numerically and experimentally. The analyses were conducted using in-house numerical methods and an in-house experimental facility for testing transonic flows. The investigations focused mainly on geometries of convergent-divergent nozzles, which best represent transonic, i.e. subsonic and supersonic, flows.

1. Introduction

Moist air is a solution (or mixture) of dry air and superheated water vapour or dry saturated vapour, or dry saturated water vapour and liquid or ice mist. Air humidity 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. During the flow through CD nozzles and due to frequent changes in parameters, shock waves may arise at the nozzle outlet. On these waves, which are mainly perpendicular, the flow parameters change dramatically. The processes of the "internal" inter-phase heat exchange in the moist air flow which are the effect of water vapour condensation and water evaporation on pressure waves are an interesting subject matter of research, both numerical and experimental.

The problem of modelling the moist air condensing flow has been the focus of attention of numerous researchers for many years. The issue is analysed theoretically and analytically in works where analytical relations on the condensation wave and the Rankine-Hugoniot relations on the shock wave are put forward for the moist air two-phase flow [1,2]. Experimental and numerical studies have also been carried out in this field. The most significant are the works of Schnerr and his research team [3–6]. They focus both on the analysis of moist air internal flows [7–10] and on aerodynamic applications, such as the flow around an aircraft wing profile for example [11]. Recent works in this field concern external flows in the first place and they are related to aerodynamic issues mainly [12].

Most works presented nowadays on the moist air flow field are based on the unsteady-state Euler and Navier-Stokes conservation equations solved in an orthogonal, curvilinear system of coordinates. This makes it possible to analyse flow phenomena in a wide range of the medium velocity, taking account of complex geometries. For many years now there have been works extending the flow model to cover viscous effects. The papers written by Heiler [9] and Winkler [10] are particularly good examples. They concern the application of the Navier-Stokes conservation equations in two-dimensional issues, but they also take transient-state phenomena into consideration. Particularly interesting results related to the transient flow are given in the paper written by Winkler [10], which presents modelling of a fluid flow through stator and rotor blades. However, the tests presented therein should be treated as tests of the method potential only because they concern a blade stage system with the same pitch for the stator and the rotor.

The applied models of two-phase flows indicate that it is possible, in the class of problems comprising flows with spontaneous

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.131
0017-9310/

Nomenclature

a	polynomial coefficient (–)
D	arc nozzle edge diameter (mm)
h	enthalpy (kJ/kg)
H^*	distance between top and bottom wall in the nozzle throat (mm)
p	pressure (Pa)
r	mean droplet size (m)
s	entropy (kJ/kg·K)
T	temperature (K)
x, y	Cartesian coordinates (m)
y	wetness mass fraction (–)
y^+	dimensionless distance of the mesh first line from the nozzle wall (–)
Φ	relative humidity (%)

Subscripts

0	total parameter
hom	homogeneous condensation

condensation in a two-dimensional geometry of the blade channel, to achieve relatively good agreement with the experiment [13,14]. This certainly encourages extension of the applied algorithms to cover more complex computational cases, such as three-dimensional flows through the turbine stages or around an aircraft wing for example.

However, the number of works extending the condensing flow model to consider three-dimensional issues is rather small due to the very limited possibility of experimental verification of such computations and the long computation times. Such spatial flow testing was performed by Singh for example [15]. The work presents a model of calculating flows through the steam turbine low-pressure stages taking account of the model of averaging parameters in the inter-rim clearance.

The Institute of Power Engineering and Turbomachinery of the Silesian University of Technology has dealt with CFD problems for about 30 years [16,17]. The works contributed to the creation of an in-house code, TraCoFlow, which enables modelling compressible flows of perfect and real gases and which is intended for compressible and transonic flows in the first place. The code is based on the URANS model.

Two-phase condensing transonic flows have been tested experimentally all over the world since the 1960s, but the research has concentrated on water vapour condensing flows mainly [18–20]. The research results have become the basis for validation of numerical methods developed since the 1990s. It may be concluded that the quality of numerical methods modelling the condensing flow of water vapour (either pure or in moist air) depends substantially on the quality and number of experimental tests performed earlier. Schnerr's experimental testing of two-phase transonic condensing flows of moist air [3] are focused mainly on the flow field visualization using the Schlieren technique and the obtained results constitute a good basis for validation of the condensation wave location and intensity in the moist air two-phase flow.

The greatest difficulty arising in the validation of developed numerical models based on experimental data available from literature is the fact that the data are incomplete – for example they do not provide sufficient information on the analysed geometry, fail to present full boundary conditions or do not ensure appropriate accuracy of the measuring quantities. This is one of the reasons why since the mid-1990s the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology has engaged in experimental testing of transonic condensing flows. Initially and for many years, the main focus of the research was the analysis of water vapour transonic flows with homo- and heterogeneous condensation [21,22]. During the works, computational models [23] and experimental techniques [13,14,24–30] were developed and perfected. Considering that atmospheric air is a common flow medium in power installations, e.g. in various kinds of power engineering machinery and equipment (compressors, ejectors, heat exchangers, etc.), implementation of the acquired knowledge for the purposes of the atmospheric (moist) air flow analysis seems fully justified.

Parallel numerical and experimental tests performed by means of in-house academic codes and laboratory installations create a great opportunity for a deeper insight into and better understanding of the flow phenomena. Moreover, the experience gained from in-house experimental testing of single- and two-phase flows enables a better assessment of the measuring data presented in literature by other researchers, for example in terms of the data uncertainty.

2. Methodology

2.1. Physical approach

Atmospheric air is moist air that always contains a certain amount of water vapour being an element of the Earth's hydrological cycle. The moisture content is most often defined using the concept of relative humidity expressed in percentages. A change in the air relative humidity occurs with a change in the air temperature – as temperature decreases isobarically, relative humidity rises to finally reach the level of 100%. This happens because as temperature gets lower, saturation pressure decreases with the water vapour constant value of partial pressure. In this case, apart from the air relative humidity and temperature, another essential quantity is the dew point value. The dew point is the temperature at which the water vapour contained in air begins to condense. The process of cooling to the dew point level occurs at a constant content of moisture. The moment that the dew point is exceeded, condensation starts and the moisture content gets smaller. In other words, the dew point temperature tells us how much moisture, at given parameters, can be absorbed by air. The dew point value in atmospheric air depends on the air relative humidity and temperature (cf. Fig. 1).

Isobaric evaporation of water droplets contained in atmospheric air takes place if the air temperature gets higher. This is a process reverse to the case described above, i.e. isobaric cooling of atmospheric air involves a rise in relative humidity until the saturation state is reached and then the process of condensation of the water vapour contained in air starts, whereas as heating proceeds, relative humidity decreases because the saturation temperature gets higher at the water vapour constant partial pressure determined by a constant value of the moisture content.

Condensation of water vapour contained in atmospheric air is also possible in technological applications without any interference from external heat sources. Adiabatic cooling is then the case, where no heat exchange with the surroundings occurs and the air