Abstract

Multiphase flows with a phase transition are ubiquitous both in the environment and in engineering. The phase transition from steam to liquid water is the best-known case of condensation. It occurs when a decrease in pressure or temperature causes steam to cross the saturation line. Condensation is important for efficient design of machinery and equipment in many industries. Traditionally, research on condensation has focused on pure steam flows. Recently, however, there has been a significant increase in interest in the condensation of air-steam mixtures. The existing numerical methods are only reliable for pure steam flows. They require further development to account for condensation in air-steam mixtures. In nature, expansion and condensation occur slowly. In expanding flows in engineering, the drop in pressure or temperature is much faster, and a thermodynamic non-equilibrium is often established. When the supercooling is strong enough, homogeneous nucleation occurs. In this case, nuclei form directly from steam. Once these nuclei reach the critical radius, they grow rapidly as the surrounding supercooled steam condenses onto the droplets. Therefore models typically rely on calibration with validation cases such as supersonic nozzle flows. Such cases of profound validation have been published for several pure steam flows, but only a few air nozzles with high expansion rates have so far been investigated.

The first goal of this work was to fill this gap. An experimental study of the humid air flow in a nozzle with a low expansion rate was carried out. It was performed for different ambient conditions for the supersonic flow and for the transonic flow, i.e. the flow in which a shock wave appears due to the flow supersonic-to-subsonic transition. The experiments were carried out using the existing low-pressure test rig at the Department of Power Engineering and Turbomachinery of the Silesian University of Technology. The stand was extended with a new test section. The experimental results provided a validation case for the considered condensation model. Moreover, the nozzle geometry with all the data is available as a benchmark test for expanding condensing flows.

The second goal of this work was a thorough analysis of the reliability of available condensation models for the humid air flow. In the past, condensation models were developed for pure steam and were not applied for studies of humid air. Nevertheless, with the increasing interest in condensation in humid air, the accuracy of the existing models was investigated. This resulted in an overview of common approaches and proved that the condensation model must not be

chosen arbitrarily. It should be selected based on the considered problem. A *blend* model, based on the kinetic molecular model and the continuous model, was distinguished because it favours the physical correctness for small droplets, while maintaining the condensation prediction for large ones.

The next goal was to study the influence of condensation on the performance of modern turbomachinery. After a reliable tool was obtained for the investigation of condensation in internal and external flows, a comprehensive study was conducted with a focus on the work of the first stage of the compressor of a turbine and the fan of a turbofan engine. It includes a numerical analysis of condensation, as well as evaporation occurring in rotating machines working on atmospheric air that contains solid and liquid suspended particles. It is shown that the phase change significantly affects the flow in the blade-to-blade channel. Condensation decreases the local velocity, whereas evaporation on the shock wave triggers opposite phenomena, leading to a shift of the shock wave downstream the flow. Together with the drop in the fluid density due to the presence of steam, which is often neglected in the numerical study of turbomachinery, this leads to significant changes in the fluid parameters at the outlet of the rotor stage. As a result, it affects the performance and efficiency of the machinery under consideration.

Finally, the Euler- and the Lagrange-based approach were compared and a superposition of both models was proposed. This demonstrates the significant impact of the numerical approach on the investigated phenomena. The pros and cons of both models are discussed and a superposition model combining the advantages of the two approaches is proposed. This shows a scientific gap which has a great potential for the development of condensing models and indicates the need for further studies.

Summing up, the results of the presented experimental and numerical analysis of condensation in expanding flows show a significant impact of the phenomenon. The phase-change phenomena lead to a local change in the flow structure, which affects the entire flow system. Both homogeneous and heterogeneous condensation might lead to a decrease in the efficiency of rotating machines and devices, which is a solid basis for the statement that phase-change phenomena have to be taken into consideration in the study and design of transonic flow systems.