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# Numerical studies of air humidity importance in the first stage rotor of turbine compressor

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**Abstract** The paper presents studies of mathematical modelling in transonic flow through the first stage rotor of the axial compressor of homogenous and heterogeneous condensation. The condensation phenomena implemented into a commercial software is based on the classical theory of nucleation and molecular-kinetic droplet growth model. Model is validated against experimental studies available in the literature regarding the flow through the first stage of turbine compressor, i.e. the rotor37 transonic compressor benchmark test. The impact of air humidity and air contamination on the condensation process for different flow conditions is examined. The influence of latent heat release due to condensation exerts a significant impact on the flow structure, thus the analysis of the air humidity and contamination influence on the condensation is presented. The results presented indicate the non-negligible influence of air humidity on the flow structure in the transonic flow regime, thus it is recommended to take condensation phenomenon under consideration in high-velocity airflow simulations.

**Keywords:** Computational fluid dynamics; Relative humidity; Condensation; Transonic flow

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# 1 Introduction

The atmospheric air, which is unquestionably one of the most common working fluids in energy and transport systems, always contain a certain amount of water and contaminations. The water is present in the air in the form of vapour or small droplets and its called the humidity. In case of transport and energy industry air is usually not being filtered or dried, thus the impact of the moisture and contaminations on the working conditions of turbomachinery and devices, hence their effectiveness, should be examined. The phenomena occurring triggered by the water dispersed in the air have been puzzling researchers for a long time. Over 30 years ago, Schnerr *et al.* [1–3], have initiated the experimental studies of humid airflow in the transonic regime, then he proposed a mathematical model based on the kinetic nucleation theorem, that was the basis for researchers all over the world, and has been implemented in many academic computational fluid dynamics (CFD) codes [4–6].

The condensation, that occurs in the transonic flow regime, can be divided due to the triggering phenomenon into homogeneous and heterogeneous condensation. The homogeneous condensation is a spontaneous process, where the nuclei appear in the flow and if the condition of the critical radius is reached, grow further, whereas the heterogeneous condensation occurs on the particles which are suspended in the air, for example, dust or sud particles. Within the sonic region, the homogeneous condensation process can occur very rapidly forming the so-called condensation wave. Within the region of the condensation shock, a high amount of latent heat is released, which significantly influences the flow structure. The heterogeneous condensation is a more gradual process, thus no shock is formed. Although the continuous water condensation on the suspended particles leads to significant growth of the diameter of the droplets. The influence of heterogeneous condensation on the flow is determined by the initial diameter of suspended particles and their number, thus it might become a major condensation process in a highly polluted air. The influence of both, homogeneous and heterogeneous condensation is strictly connected with the air humidity. The air humidity is usually given as a non-dimensional number, the relative humidity, that is the actual amount of water vapour in reference to the maximum amount of water vapour that air can contain. The amount of water that can be carried by air in the form of vapour grows with its temperature. The typical value of relative humidity is in the range between 40% and 50%, however, in certain conditions, it can reach the value of up to 90%. Therefore it is recommended to take both phenomena into account in the simulation of flow in the transonic regime.

Phenomena of phase change in the transonic flow have been encouraging researchers to investigate this phenomenon in external and internal flow. Research regarding the transonic internal flow of humid air initiated by Schneer *et al.* [6] has become a base and reference for further research. Valuable experimental and numerical studies were conducted by Adam, who investigated the non-stationarity of the flow induced by the interaction of condensation wave with the shock wave. In his work, he investigated the frequency of oscillation related to the relative humidity in a nozzle with parallel walls. Dykas and co-workers have developed an academic code, which has been recently implemented into the commercial software, in which the humid air and water droplets are treated as homogeneous fluid. The developed codes demonstrate good convergence with the in-house experimental studies and experimental data available in the literature regarding the internal and external flow of humid air [4, 7–9]. The simulations of the condensation in the transonic flow are highly computational power demanding, however the Moriguchi *et al.* shows that it is possible to investigate a humid airflow in the whole compressor rotor with a non-uniform circumferential humidity distribution [10]. The majority of numerical studies are carried with the use of single fluid models, these type of models treat the humid air and water droplets as continuous, homogeneous fluid. This approach is reasonable if the water droplets are small, thus the inertia does not affect the flow significantly. Although in case of the flow with a high swirl, i.e. flow through compressor rotor or turbine rotor, the interphase momentum exchange becomes significant. Moreover, if the conditions are suitable for droplets growth to a significant size the inertia also can exert a non-negligible influence on the flow structure. The attempts of multi-fluid models of wet steam and humid air have started to appear [11, 12]. Ding *et al.* [13] have developed a numerical model of the multi-fluid model and used it to investigate the performance of supersonic dehydrator, in which the drying process is forced by homogeneous and heterogeneous condensation . A significant contribution to the development of numerical simulations regarding complex 3D flow structures has been done by Yamamoto [14, 15]. The studies of multiphase flow are in major importance in turbomachinery, where the liquid phase may lead to performances drop and cause mechanical issues. The numerical studies regarding dehumidification strategy for nuclear power plant turbine were conducted by Zhang *et al.* [16–19], however, the working fluid was wet steam instead of humid air, which indicates the possibility of such crucial studies.

This paper presents a numerical study of condensation influence on the performance of the first stage compressor rotor. The studies are performed using commercial CFD software Ansys Fluent [28] with use of the user defined functions (UDFs). The influence of air temperature and humidity on the performance is presented. The paper shows the need for the importance of humidity on the working condition and the need for further studies regarding this crucial phenomenon.

## 2 Numerical model

The studies were conducted with the use of commercial software Ansys Fluent [28]. The flow conservation equations are formulated for the compressible flow with the use of Unsteady Reynolds-averaged Navier–Stokes (URANS) equations. The air, water vapour and water droplets are treated as a continuous, homogeneous mixture, i.e. there is no slip velocity between phases.

With the use of UDF's, the governing equations are expanded of proper source terms connected with the latent heat release and three additional governing equations describing the mass fraction of water due to homogeneous condensation and number of droplets due to nucleation inhomogeneous condensation process. The phenomenon occurring in transonic flow with phase change is strongly influenced by the viscous forces, therefore the $k$-$\omega$ SST (shear–stress–transport) model proposed by Menter [20] was used to model the turbulence effect.

The condensation process has been implemented into the software using UDFs. The homogeneous condensation phenomenon is based on the kinetic gas theory. The triggering phenomenon of homogeneous condensation is the nucleation process. The nuclei form spontaneously and grow further if the condition of the critical radius is fulfilled. The critical radius is given by the form of the Kelvin equation [21]. The nucleation process is based on the classical nucleation theory, in which the Kantorowitz correction is considered [22]. The growth of the droplets due to the homogeneous condensation process is described employing the molecular-kinetic droplet growth theory [23].

For more information regarding the implementation, numerical techniques and solver settings we refer the reader to our previous papers, where the 2D studies of condensation in converging-diverging nozzles and the oscillation phenomenon are shown [4, 7–9, 24].

# 3 Numerical studies

## 3.1 Validation

Validation of the condensation model considering the 2D internal and external flows of humid air was performed by authors and it is described in the previous paper [8]. In this paper, authors focus on the studies regarding the 3D flow of humid air in the first stage of the compressor rotor of a turbine engine. The considered case study, NASA rotor37, is based on the literature data, which provides the data of geometrical shape and working conditions [25]. As the studies are focused on the influence of the condensation phenomenon on the flow structure and not on the precision of turbomachinery simulation, it was considered reasonable to omit the tip clearance effect. The mesh of ~1 300 000 elements was created, the boundary layer was introduced to guarantee the $y^+$ (non-dimensional wall normal distance) function value about 1, see Fig. 1. Figure 2 shows the pitchwise averaged ratio of total pressure, $p_t$, to inlet total pressure, $p_{0t}$, at section 4 (ST4), that is 0.1067 m downstream of the blade hub leading-edge, obtained with the use of the numerical tool in comparison to the experimental data [26], where $l$ is the blade height.

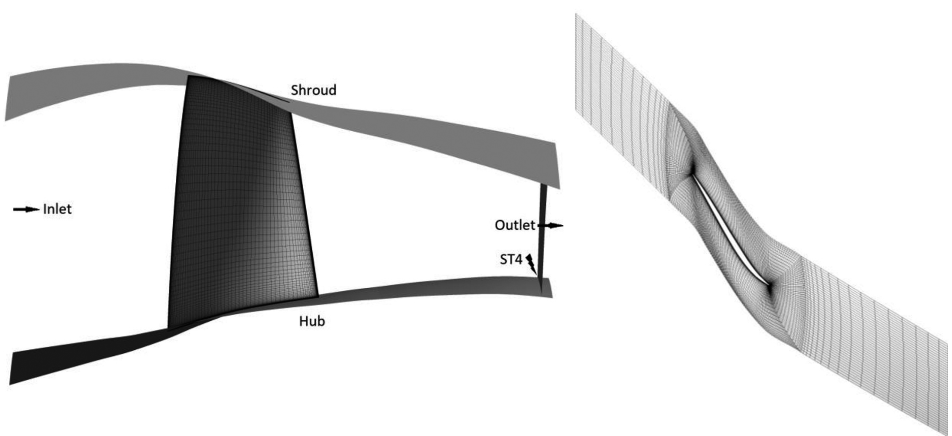


Figure 1: The domain with highlighted blade mesh and the ST4 (left). The mesh at 80% of the blade span (right).

The mass flow rate, $\dot{m}$, the total pressure ratio, $p_t$, and the total temperature ratio, $T_t$, based on the experimental and numerical studies are

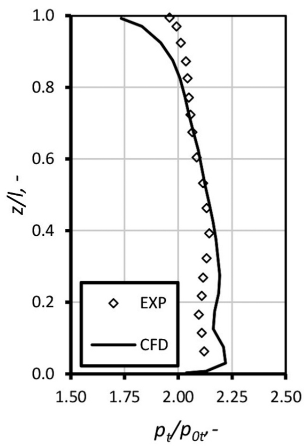


Figure 2: Pitchwise averaged ratio of total pressure to inlet total pressure for rotor37 at ST4.

shown in Table 1, the discrepancy of results for rotor37 is less than 1.5% and might be caused by the tip clearance neglecting in numerical considerations. The good convergence of the results justifies the use of the presented model in further studies.

Table 1: The experimental and numerical mass flow rate, total pressure and total temperature ratio for NASA rotor37.

| | $\dot{m}$, kg/s | $p_t/p_{0t}$, – | $T_t/T_{0t}$, – |
|---|---|---|---|
| EXP | 20.19 | 2.11 | 1.27 |
| CFD | 20.41 | 2.09 | 1.27 |

## 3.2 Condensation studies

The studies of pure homogeneous condensation were performed to define the influence of air humidity on the flow structure, thus the studies were performed for the relative humidity, $\varphi = 70\%$ and total temperature at the inlet boundary condition equals to 273 K, 288 K, and 303 K. Figure 3, shows the influence of air total temperature, while maintaining the relative humidity value, on the pressure distribution at the ST4. The condensation occurs mainly in the area near to the rotor hub and rotor blades and for considered conditions it has a minor impact on the flow structure.

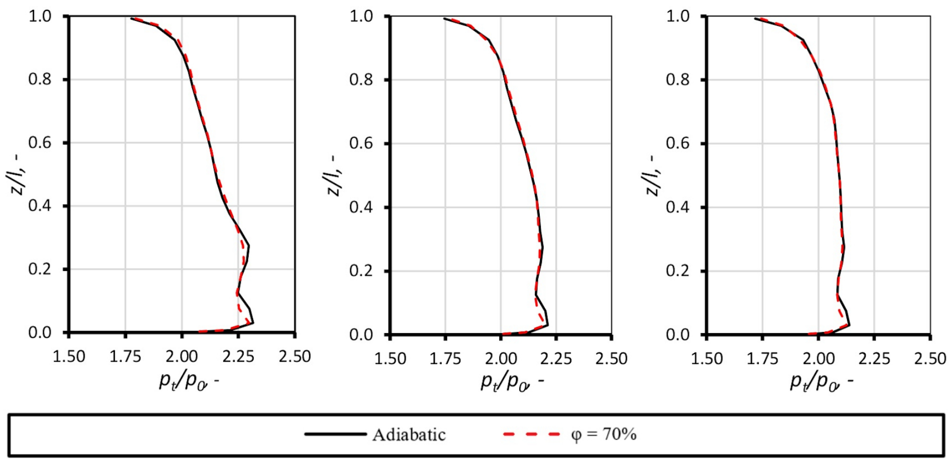


Figure 3: The influence of air humidity on the total pressure ratio at ST4, in comparison to adiabatic flow, with inlet total temperature equal to 273 K, 288 K and 303 K.

The influence of heterogeneous condensation is more significant than the influence of pure homogeneous condensation. The heterogeneous condensation occurs in an initial part of the compressor rotor. Its studies were performed for 4 different cases which differs one from another by the number of suspended particles, $n_{het}$, and their initial radius, $r_{het}$. The values of the number of droplets and their diameter at the inlet boundary conditions are shown in Table 2. Figure 4 shows the influence of contamination on total pressure distribution at ST4. The increase of the number of suspended particles and their radius strongly influence the flow by increasing the losses. The mass fraction of water condensed due to heterogeneous condensation is depicted in Fig. 5. As it can be observed with the increment of the number of particles the mass fraction of condensed water increases.

Table 2: Cases for heterogeneous condensation studies.

| Case | $n_{het}$, $\frac{1}{\text{kg}}$ | $r_{het}$, m |
|---|---|---|
| Het1 | $10^{14}$ | $1 \times 10^{-8}$ |
| Het2 | $10^{14}$ | $1 \times 10^{-7}$ |
| Het3 | $10^{15}$ | $1 \times 10^{-8}$ |
| Het4 | $10^{15}$ | $1 \times 10^{-7}$ |

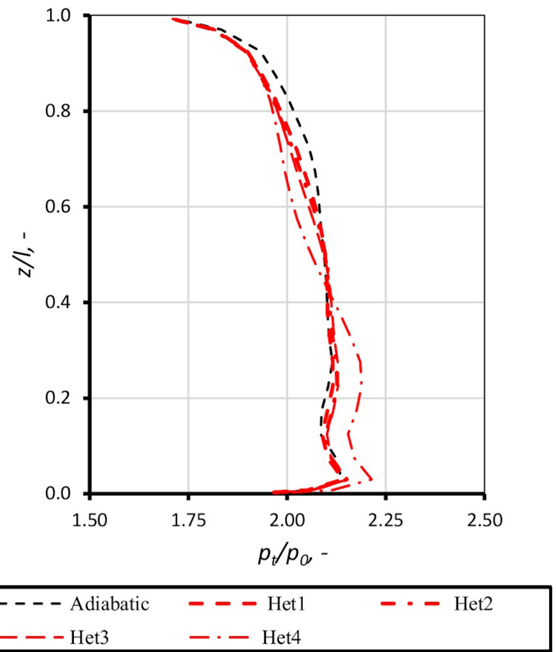


Figure 4: The influence of the number of suspended particles and their radius on the total pressure ratio at ST4, in comparison to adiabatic flow, with inlet total temperature equal to 303 K.

Figure 6 presents the influence of condensation on the velocity vectors for the Het4 case and adiabatic case. Table 3 shows the comparison of velocity angles and the mass flow rate for all cases at different spans at the ST4.

Table 3: The influence of heterogeneous condensation on the velocity angles and mass flow rate value at ST4.

| | $\alpha$, ° | | | $\beta$, ° | | |
|---|---|---|---|---|---|---|
| | Span | | | Span | | |
| | 0.2 | 0.5 | 0.8 | 0.2 | 0.5 | 0.8 |
| Adiabatic | 38.46 | 39.36 | 39.07 | 31.12 | 36.61 | 43.70 |
| Het1 | 38.39 | 39.45 | 40.62 | 30.69 | 36.47 | 44.56 |
| Het2 | 38.38 | 39.41 | 40.89 | 30.48 | 36.57 | 44.84 |
| Het3 | 38.50 | 39.48 | 41.12 | 30.26 | 36.64 | 44.76 |
| Het4 | 38.32 | 39.23 | 42.60 | 30.21 | 38.39 | 45.95 |

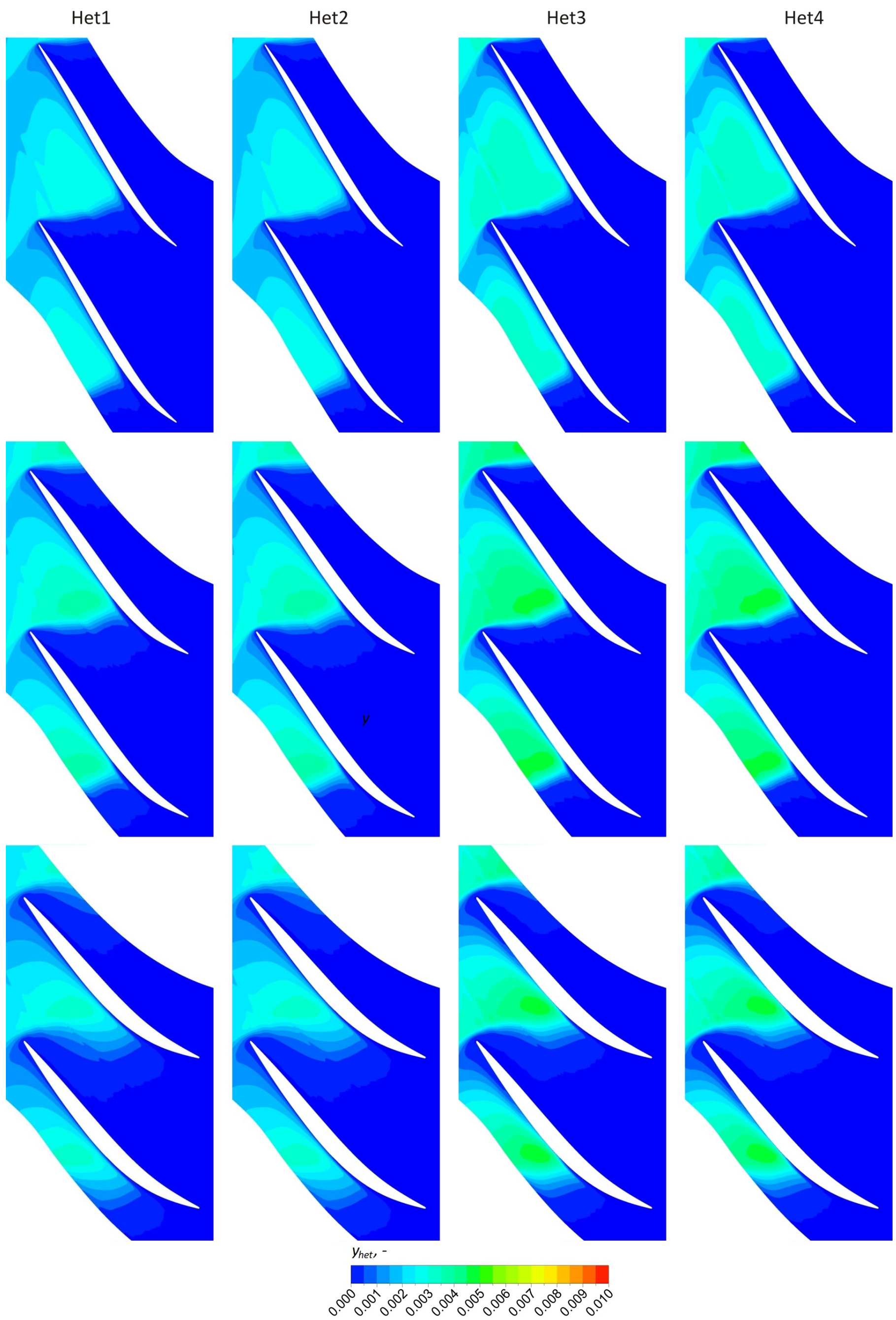


Figure 5: Mass fraction of water condensed due to heterogeneous condensation for the span from top to bottom respectively 0.8, 0.5 and 0.2.

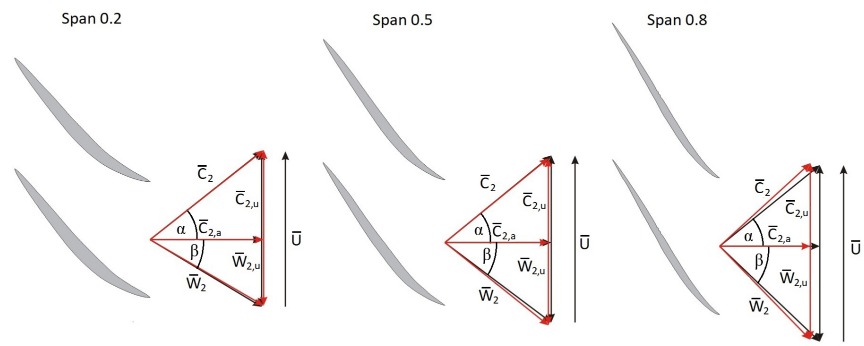


Figure 6: The influence of condensation, case HET4, on velocity vectors at ST4.

# 4 Conclusions

Turbomachinery flows are strongly three-dimensional and are characterized by many complex physical phenomena. With the use of the newest Hi-Fi (high fidelity) computational fluid dynamics tools, the turbomachinery flow can be faithfully reflected. However, the modern CFD tools still have some areas that need further development, one of these is the moist air flow. In this paper, numerical studies regarding the condensation phenomenon in the transonic flow regime through the blade to blade rotor channel in the first stage of the compressor is presented. Conducted numerical studies present the inlet temperature and air humidity importance in the case of turbomachinery simulations. The major importance of the latent heat release due to the condensation phenomenon occurring in the transonic region of the flow has been indicated. The importance of air contamination is highlighted by the authors. Although in considered conditions the pure homogeneous condensation does not exert a significant impact on the flow structure, the heterogeneous condensation influence is non-negligible. The influence of condensation occurring on the particles suspended in the air is strictly connected with their number and radius. The condensation does not only affect the total parameters of the flow, it also affects the velocity field. An interesting area to further investigation is the slip velocity between phases. In conducted studies, the slip velocity was neglected. Although, if the droplets grow to relatively large size, for example, due to heterogeneous condensation, the inertia forces might exert an important influence on the flow structure.

Summing up, the paper shows the influence of air humidity and pollution on the flow structure in a turbine's compressor rotor. It is stressed that the influence of both homogeneous and heterogeneous condensations should be taken into consideration during the design process. The results presented give an overall view in the process of phase change inside the blade do blade channels and highlight that further studies of this phenomenon are needed.

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