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# Numerical study of non-equilibrium condensation and shock waves in transonic moist-air and steam flows

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ABSTRACT

Transonic condensing/evaporating moist-air flow through converging-diverging nozzles is investigated numerically using non-equilibrium thermodynamic model. In this study, the results of moist-air and pure steam flows through nozzles are compared, in other words, carrier gas effects are investigated numerically. It is observed that, under similar operating conditions for steam, the wetness fraction and droplet nucleation rate along the nozzle in the case of moist-air flow is more than pure steam case. That is due to the internal flow of heat from steam portion towards the air that enhances the wetness fraction and droplet nucleation rate in moist-air case. In this study, the influence of the normal aerodynamic shocks is also studied. It is interestingly observed that, although the entropy of the mixture (steam+air) and steam portion increases along the shock, the entropy of the air portion can be reduced in response to evaporation of the liquid phase. Validation of the results is performed versus the experimental data for pure steam and moist-air flows, which show relatively good agreements.

## 1. Introduction

Condensation phenomena in compressible pure steam or moist-air flows have been traditionally studied because of its industrial applications. Examples include flows in vapor nozzles, rocket motors, steam turbines, aircraft wing surfaces and many more. Below a review of condensation phenomena in pure steam and moist air flows is given.

**Condensation in pure steam cases:** In the case of transonic pure steam flow; Moore et al. [1] have presented an experimental data for condensing steam flow in low pressure nozzles. Bakhtar and Zidi [2,3] have studied the non-equilibrium condensation in high pressure cases both experimentally and theoretically. Kermani and Gerber [4,5] have performed some numerical studies in nozzles and cascades of steam turbines using non-equilibrium thermodynamic model. Luo et al. [6] have done one dimensional calculations for spontaneously nucleating flows of steam by space–time CESE method. Halama et al. [7,8] have done some numerical studies on steady and unsteady condensing/evaporating steam flow in nozzles and cascades of steam turbines. Recently Dykas and Wroblewski [9] have performed some numerical computations for condensing steam flow in low and high pressure nozzles.

**Condensation in moist-air cases:** Moist-air is a mixture of water vapor and air. Condensation of the moist-air occurs in the aeronautical sciences for example airplanes, helicopter airfoils, nozzles, etc. Various tests on transonic moist-air flow in nozzles, wind tunnels and around airfoils have been done by Pouring [10]. The results showed that, the condensation phenomena can affect on the aerothermodynamics behavior of the moist-air flow. Condensing/evaporating flows around airfoils have studied by Schnerr and Dohrmann [11,12]. The results show that the heat transfer as a result of the condensation or evaporation of the moist-air affects on the flow properties, specifically the pressure distribution along the surfaces of the airfoil. The non-equilibrium and homogeneous condensation of moist-air around thin airfoil by a small-disturbance model have studied by Rusak and Lee [13]. Yamamoto [14] developed a preconditioned flux–vector splitting (PFVS) scheme in general curvilinear coordinates for condensing moist-air flow. The numerical and experimental studies of heterogeneous condensation of moist-air flow in cooled pipe are done by Sakakura and Yamamoto [15]. Toufique Hasan et al. [16] have done some numerical studies of transonic condensing moist-air flow with shock waves around a symmetric disk using non-equilibrium condensation and the results are compared with results of dry air.

Recently we have performed some numerical computations of moist-air flow using equilibrium thermodynamic model through converging-diverging nozzles [17,18]. In these papers, the wetness fraction in the case of moist-air flow is compared with that of

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## Nomenclature

| | | |
|---|---|---|
| $A$ | Area | $m^2$ |
| $c_{p,a}$ | Air isobaric specific heat | J/kg K |
| $c_{p,v}$ | Vapor isobaric specific heat | J/kg K |
| $c_{v,a}$ | Air isochoric specific heat | J/kg K |
| $c_{v,v}$ | Vapor isochoric specific heat | J/kg K |
| $e$ | Internal energy | J/kg |
| $h$ | Enthalpy | J/kg |
| $J$ | Nucleation rate | # droplets/$m^3$ s |
| $k$ | Boltzmann's constant ($= 1.3807 \times 10^{-23}$ J/K) | |
| $m$ | Mass of one molecule of water | kg |
| $M$ | Mach number | |
| $\dot{m}$ | Mass flow rate | kg/s |
| $P$ | Pressure | Pa |
| $q$ | Primitive variable | |
| $Q_0, Q_1, Q_2$ | Hill's moments | |
| $r$ | Average radius of droplets | m |
| $r_c$ | Droplet critical radius | m |
| $R$ | Gas constant | J/kg K |
| $\dot{r}$ | Radius growth rate | m/s |
| $s$ | Entropy (J/kg K) or super saturation ratio | |
| $t$ | Time coordinate | s |
| $T$ | Temperature | K |
| $u$ | Velocity | m/s |
| $x$ | Spatial dimension | m |

*Greek symbols*

| | | |
|---|---|---|
| $\beta$ | Liquid mass fraction | |
| $\gamma$ | Specific heat ratio | |
| $\eta$ | Correction parameter | |
| $\rho$ | Density | kg/$m^3$ |
| $\chi$ | Quality of steam | |
| $\omega$ | Humidity ratio | |
| $\sigma$ | Surface tension | N/m |

*Subscripts*

| | |
|---|---|
| $a$ | Air |
| $E$ | East face of control volume |
| $f$ | Saturation liquid |
| $fg$ | Interval of latent heat |
| $g$ | Saturation vapor |
| $l$ | Liquid |
| $mix$ | Mixture (air + steam) |
| $res$ | Reservoir |
| $s$ | Steam or saturated state |
| $v$ | Vapor |
| $W$ | West face of control volume |
| $0$ | Stagnation condition |

*Superscripts*

| | |
|---|---|
| $L$ | Left side of east cell face |
| $n$ | Time level |
| $R$ | Right side of east cell face |
| $\widehat{\ }$ | Roe's averaged state |

pure steam case. It was observed that, under similar operating conditions for steam portion, in the case of moist-air flow through nozzle, condensation begins earlier than that of the pure steam case and the wetness fraction along the nozzles in the case of moist-air flow is more than that of pure steam case. The results also show that the wetness fraction can affect on the aerothermodynamics behavior of the moist-air flow e.g. shock angles [18].

**The focus of the present study:** In the present research, the results of our earlier computations using equilibrium thermodynamic model [17,18] is extended to non-equilibrium thermodynamic model applications. In equilibrium thermodynamic model the condensation will occur when the temperature is infinitesimally below the saturation temperature corresponding to the prevailing pressure. In contrast, in rapid expansion of pure steam or moist-air flow a non-equilibrium condensation usually occurs. In non-equilibrium thermodynamic model (which happens in reality) condensation does not occur on a saturation line, it rather occurs when a super saturation ratio ($P_v/P_{sat}$, where $P_{sat}$ is the saturation pressure and $P_v$ is the vapor pressure) or a supercooling level ($T_{sat} - T$, where $T_{sat}$ is the saturation temperature and $T$ is the vapor temperature) reaches a critical (maximum) value. Afterward, condensation takes place by spontaneous nucleation of tiny liquid droplets. The high rate of heat release, as a result of rapid condensation, causes a sharp increase in pressure known as condensation shock. The condensation shock which occurs in reality cannot be seen in the equilibrium thermodynamic model [17,18].

As the contribution of the present paper, the results of an earlier computation of the Roe scheme [19] for the two phase moist-air flow using equilibrium thermodynamic model [17,18] is extended to the non-equilibrium thermodynamic model applications. Also, the governing equations and the corresponding extended code employed in this paper can also predict the behavior of nucleating pure steam and moist-air flows with satisfactory precision. The present work improves the accuracy of our earlier results [17,18] for transonic pure steam and moist-air flows by extending the computational code from equilibrium thermodynamic model to non-equilibrium thermodynamic model. In comparison with equilibrium thermodynamic model, results of non-equilibrium thermodynamic model show better agreement with experimental data.

In the present work, the content of condensate generation in moist-air case is also compared with that of pure steam. The same as equilibrium thermodynamic model [17,18], it was observed that in the case of moist-air flow through nozzle the content of generated condensate is much higher than that of pure steam flow under similar operating conditions (about 4–5 times more in the present case). That is in well agreement with our earlier predictions in equilibrium thermodynamic model (see [17,18]). In the case of non-equilibrium thermodynamic model, it is also observed that, further wetness fraction, the droplet nucleation rate in the case of moist-air flow is more than pure steam case. Here wetness is defined as the mass fraction of the liquid water to that of the steam, where steam is the mixture of liquid water + water vapor in wet regions. The results show that, due to the condensation shock in the present model, the entropy of the mixture increases. In this research the influence of the normal aerodynamic shock in transonic moist-air flow is investigated. The results reveal that the liquid phase evaporates across the normal shock. Also, it is interestingly observed that, although the entropy of the mixture (steam + air) and steam portion increases along the shock, the entropy of the air portion can reduce in response to evaporation of the liquid phase.

## 2. Governing equations

The assumptions which are used in the present study for the two phase flow are as follows: the velocity slip and temperature differences between condensate particles and gas mixture are neglected, condensation is homogeneous, volume of droplets is neglected, and the condensing moist-air flow is assumed to be invis-