Evaporation level of the condensate droplets on a shock wave in the IMP PAN nozzle depending on the inlet conditions

S Kornet¹ and J Badur¹

¹The Szewalski Institute of Fluid-Flow Machinery PAS-ci, Energy Conversion Department, Fiszera 14, 18-231 Gdansk, Poland

E-mail: skornet@imp.gda.pl, jb@imp.gda.pl

Abstract. In the present paper we have focused on the phenomena of condensate re-evaporation in the shock wave zone. Having observed the finishing of a foggy flow within the shock wave, according to Puzyrewski’s observations, we would like to analyse the critical inlet conditions which cause total evaporation of condensate droplets on the shock in the IMP PAN nozzle. In the paper some original mechanistic model of droplet evaporation is involved, numerically implemented and compared with the IMP PAN experiment. The single continuum model of wet steam with a special microstructure growing up during phase transitions was validated on IMP PAN experiment performed for inlet conditions close to the saturation line. The present work includes simulations results of total and partial evaporation liquid phase on the shock wave for different boundary conditions.

1. Introduction

In the space between the turbine blades, which resembles the shape of the de Laval nozzle, the shock wave can appear, which has a negative impact on the flow of the steam [1]. If a supersonic flow passes through a duct of certain length, under certain conditions, successive shocks can appear downstream of the first shock. This series of shocks is a so-called shock train [2, 3]. The shock train in the IMP PAN nozzle obtained from CFD simulations is shown in figure 1.

Figure 1. Typical shock train in supersonic part of the IMP PAN nozzle.

Shock wave is the result of interaction between a normal shock wave and the boundary layer, which produces a $\lambda$-foot structure. It is well-know and experimentally confirmed that for high flow velocities (Ma > 1.4) the $\lambda$-feet generated on the side walls of the symmetric nozzle become different in size. It has also been observed that the tendency towards asymmetry depends on the nozzle divergence angle and the walls roughnesses [7, 8, 9, 10, 13, 14]. This asymmetry does not flip during an experiment but may change sides from one experiment to the next one [11, 12].
According to Puzyrewski’s observations, partial or total evaporation of the condensate droplets in the shock wave zone is possible and depends on the boundary conditions and the thermodynamic conditions in divergent part of the nozzle [1, 4, 5].

In this paper we have focused on the precise prediction of the critical inlet temperature above which occurs total evaporation of condensate on the shock. In our model, the evaporation is governed not only by mass transport but also by internal structure energy that is based on balance of heat energy transported into a droplet. Numerical analysis was performed on the IMP PAN nozzle. The present work includes simulations results of the critical inlet temperatures which determine the border between total and partial evaporation on the shock wave. Calculations were performed for set of various inlet pressures with keeping the same value of pressure ratio for each case.

2. Single continuum model of wet steam

A wet steam model include governing equations which are based on balance of liquid-vapour mixture. For a consistent non-equilibrium condensation model a set of nine transport equations can be written in general form [1, 5, 6, 15]:

\[ \partial_t (\rho \phi) + \text{div}(\rho \phi \mathbf{v}) = \text{div}(\mathbf{J}_\phi) + \rho S_\phi \]

(1)

where: \( \phi = \{1, v, e, k, \epsilon, x, a\} \) represents the relevant conserved variable. First three variables in \( \phi \) set come from well know equations: balance of mass \((\phi = 1)\), balance of momentum \((\phi = v \text{ - three equations})\), balance of energy \((\phi = e)\). The rest of variables include in \( \phi \) set are explained in paragraph 2.1. Process of growth of individual droplet is governed by mass, momentum and energy transport mechanism between gas and liquid phases. Droplet growth can be described by an evolution of radius of droplet that moves in the wet steam field. Evolution equation of dryness fraction is given by:

\[ \partial_t (\rho x) + \text{div}(\rho x \mathbf{v}) = \text{div}(\mathbf{J}_x) + \rho S_x \]

(2)

The dryness fraction sources \( S_x \) (in equation (2)) can be divided into homo- and heterogeneous sources of the mass generation rate due to condensation and evaporation. Homogenous source includes part responsible for inception of droplets and part responsible for growth and evaporation of droplets:

\[ S_x = \frac{4}{3} \Pi \rho \_r^3 l + 4 \Pi \rho \_r^3 \_l \frac{\partial r}{\partial t} \]

(3)

where: \( r \) - an average radius of droplet [m], \( \rho \_r \) - density of condensed phase [kg/m\(^3\)], \( r \_c \) - the critical radius of droplet [m], \( l \) - a volumetric rate of nucleation [number of droplets/m\(^3\)], \( \_l \) - volume fraction of condensate [-][1, 5, 6, 15].

2.1. Interaction of turbulent and phase microstructure

In our approach the phase microstructure has similar size like the turbulent microstructure which evaluate under following concept: according to possible splitting of modes of momentum transport only two scalar parameters can describe a evolution of turbulent microstructure, e.i. the turbulent energy \( k \) and the turbulent dissipation \( \epsilon \). The evolution equation for turbulent microstructure has a following form:

\[ \partial_t (\rho k) + \text{div}(\rho k \mathbf{v}) = \text{div}(\mathbf{J}_k) + \rho S_k \]

(4)

\[ \partial_t (\rho \epsilon) + \text{div}(\rho \epsilon \mathbf{v}) = \text{div}(\mathbf{J}_\epsilon) + \rho S_\epsilon \]

(5)
Transport of non-equilibrium properties between the phase and turbulent microstructure can be made directly on the microstructure level, without exploring the total momentum equation. It may be done by introducing the crossing effects in phase and turbulence fluxes [6, 16, 17]:

- Turbulent kinetic energy \( k \) [m\(^2\)/s\(^2\)]:
  \[
  J_k = (D_{k\infty} + D_{k\rho}) \nabla k + (D_{k\omega} + D_{k\omega}) \nabla x
  \]  
  \( J \) (6)

- Dryness fraction \( x \) [-]:
  \[
  J_x = (D_{x\infty} + D_{x\rho}) \nabla k + (D_{x\omega} + D_{x\omega}) \nabla x
  \]  
  \( J \) (7)

- Turbulent energy dissipation rate \( \varepsilon \) [m\(^2\)/s\(^3\)]:
  \[
  J_\varepsilon = (D_{\varepsilon\infty} + D_{\varepsilon\rho}) \nabla \varepsilon + (D_{\varepsilon\omega} + D_{\varepsilon\omega}) \nabla \alpha
  \]  
  \( J \) (8)

- Interphase surface density \( \alpha \) [m\(^2\)/m\(^3\)]:
  \[
  J_\alpha = (D_{\alpha\infty} + D_{\alpha\rho}) \nabla \varepsilon + (D_{\alpha\omega} + D_{\alpha\omega}) \nabla \alpha
  \]  
  \( J \) (9)

Diffusion coefficients \( D \), which are related with homogeneous diffusion known as the Ostwald mode (subscript \( \rho \)) and heterogeneous condensation mode (subscript \( \omega \)) need estimations and calibrations [1, 6, 17].

3. Validation of wet steam model by comparison with the experiment data
The model of a single continuum with a special microstructure growing up during phase transitions, proposed by Bilicki and Badur [6], was validated on the IMP PAN experiment carried out by Puzyrewski. The experiment was carried out on a symmetric nozzle of “rectangular” cross-section. The nozzle shape and 3D FVM model are shown in figure 2.

Figure 2. IMP PAN nozzle: a) shape and dimension, b) FVM discretization.

3.1. Boundary conditions of the IMP PAN experiment
To validation of CFD model selected boundary conditions which correspond to the V-th set of experimental conditions. The inlet pressure was \( p_{inlet} = 2.26 \) bar, the inlet temperature \( T_{inlet} = 502 \) K. Pressure at the point of intersection of the isentropic expansion line and saturation line was \( p_{sat} = 0.55 \) bar. These input conditions were close to the saturation line in order to obtain a condensation [4]. The static pressure during experiment was measurement on both side walls in sixteen points on each from wall (see figure 2a).

3.2. CFD results and comparison with the test data
For a given the de Laval nozzle (IMP PAN nozzle) geometry authors have conducted calculations for the single continuum model of wet steam. Figure 3 shows a comparison of the static pressure distribution obtained from numerical simulation with IMP PAN experimental data (for V-th set of boundary conditions[4]). For this case we obtained total evaporation of the condensate during passage
through the strong shock what agree with experimental results: *For V-th set of experimental conditions, there were only very slight traces of mist ahead of the shock wave, disappearing in the shock.* The wet steam model of a single continuum, describing both condensation and re-vaporization, applied to the de Laval nozzle gives satisfactory results that agree well with experimental data (very well describes static pressure distribution and prediction of the shock wave).

**Figure 3.** Comparison of the static pressure distributions along nozzle wall obtained from CFD calculations with experimental data.

4. **Numerical analysis of the evaporation level of condensate droplets on the shock wave in the IMP PAN nozzle**

Having observed full evaporation phenomena on the strong shock wave, according to Puzyrewski’s observations (see figure 4 – more details can be find in [4]), it was decided carried out numerical analysis of the evaporation level on the shock in the IMP PAN nozzle depending on the inlet conditions. All geometry of the nozzle was splitted on nine subdomains what contributed to created the higher quality mesh (see figure 2b). For first step of simulation it was decided to decrease the grid spacing only in zones close to the inlet and close to the outlet of the channel. After having determined the position of the shock wave appearing in the flow and the oscillation zone in next steps increased the grid resolution in this places. Additionally decreased the size of the finite volume upstream and downstream of the oscillation zone. When the results in next step were the same (or approximately the same) as in previous step the modify of the mesh was ceased. These steps were used for each considered case of the boundary conditions.

**Figure 4.** Evaporation of condensate droplets during passage through the shock wave [4]

4.1. **Boundary conditions adopted to the numerical analysis**

To numerical analysis adopted four different values of the inlet pressure: \( p_{\text{inlet}} = 2.5 \), \( p_{\text{inlet}} = 3 \), \( p_{\text{inlet}} = 3.5 \) and \( p_{\text{inlet}} = 4 \) bar. For each case of the inlet pressure carried out simulations with five different values of the inlet temperature: \( T_{\text{inlet}} = 450; 440; 430; 420; 410 \) K. The pressure ratio, in each considered case, was equal to \( p_{\text{inlet}} / p_{\text{outlet}} = (p_{\text{tot}} + p_{\text{atm}})/(p_{\text{stat}} + p_{\text{atm}}) = 1.7 \), where \( p_{\text{atm}} = 101325 \) Pa. In the calculation it was assumed that steam is chemically very pure.
4.2. Results and discussion
The position of the nucleation zone mostly depended on the inlet temperature and the purity of steam. The effect of the inlet temperature on moving of the nucleation zone was analyzed by using CFD model in [18] based on the test data. For each case of the inlet pressure the nucleation zone is shifted to the nozzle entry with decreasing value of the inlet temperature. Calculated wetness fractions for different inlet temperatures and for the inlet pressure 2.5 and 4 bar are shown in figures 5 and 6 respectively. In each case of the inlet conditions the condensate mostly evaporate during passage through the Mach disc (in main flow zone). The evaporation level on the oblique shocks is lower than the evaporation level on the Mach disc. For the inlet pressure equal to 4 bar the value of wetness fraction upstream the shock is bigger than for the inlet pressure equal to 2.5 bar. The expansion line for the case with lower value of the inlet pressure is shifted to the right on i-s diagram. This means that for this case for bigger pressure expansion the saturation line will be exceeded. Therefore position of the nucleation zone for smaller inlet pressure is shifted to the nozzle exit and wetness fraction is lower. For cases of the inlet conditions which relate to conditions of wet steam on i-s diagram adopted that steam for these cases is sub-cooled and in metastable state. This assumption and assumption that steam is very pure means that on the nozzle inlet there doesn’t exist two-phase flow.

In all cases smaller $\lambda$-feet is generated on a upper wall of the nozzle because all simulations were carried out by using one initialization. Of course during calculations with new initializations the asymmetry may change sides (as during new experiment [11, 12]), but for better comparisons it was decided show results for the same type of asymmetry.

![Figure 5. Calculated wetness fraction ($y = 1-x$) for the inlet pressure 2.5 bar and different values of the inlet temperature.](image1)

![Figure 6. Calculated wetness fraction ($y = 1-x$) for the inlet pressure 4 bar and different values of the inlet temperature.](image2)
this way are shown in figures 7-10. Red part of the solid line in figure 7 correspond to very short part of the virtual line (about 3-3.5 mm) which crosses the normal shock. Very strong steam compression on the shock and increase of steam temperature on very short distance can explain the shape of this part of curve (and shapes of curves in the places passage through the shock wave for other cases). For each case of the inlet pressure the expansion line on “i-s” diagram is shifted to the left with decreasing inlet temperature. For each case there is a jump of steam conditions caused by the shock wave which appears in supersonic part of the nozzle. In cases with bigger value of the inlet temperature there is a small peak in the wet steam zone (before reaching the lowest position) which determines start condensation of the supercooled water vapour. During condensation the thermal energy is transported from liquid droplets to the gas phase what can explain the direction and shapes of observed peaks.

**Figure 7.** Change of steam entropy during nozzle expansion for case $p_{inlet} = 2.5$ bar.

**Figure 8.** Change of steam entropy during nozzle expansion for case $p_{inlet} = 3$ bar.

**Figure 9.** Change of steam entropy during nozzle expansion for case $p_{inlet} = 3.5$ bar.

**Figure 10.** Change of steam entropy during nozzle expansion for case $p_{inlet} = 4$ bar.
In this work authors assumed that the evaporation level will be measured during passage through the Mach disc. For this purpose, for each considered case, appointed the values of the wetness fraction upstream and downstream the normal shock. In table 1 are presented the results of the evaporation level for all considered cases of the boundary conditions. In our approach the level of condensate evaporation on the shock wave is described under following concept: to show how big part of exist liquid phase located upstream the shock evaporate during passage through the Mach disc or the normal shock. Therefore results are presented in %. As expected the evaporation level increases with increase the value of the inlet temperature. During comparison results from “i-s” diagrams with results from table 1 we can note some differences. This differences results from definition of wetness fraction (or dryness fraction). On diagrams we have shown values of dryness fraction calculated as equilibrium while the evaporation level was computed by using non-equilibrium definition of the wetness fraction. In each case of the steam flow in the IMP PAN nozzle occurs phenomena called spontaneous condensation and phenomena “spontaneous evaporation”. Differences between non-equilibrium and equilibrium values of the dryness fraction for case \( p_{inlet} = 4 \text{ bar} \) and \( T_{inlet} = 410 \text{ K} \) along virtual line are shown in figure 11.

### Table 1. Evaporation level on the Mach disc for all considered boundary conditions

| \( T_{inlet} \) [K] | \( p_{inlet} \) [bar] | Evaporation level [%] | \( p_{inlet} \) [bar] | Evaporation level [%] | \( p_{inlet} \) [bar] | Evaporation level [%] | \( p_{inlet} \) [bar] | Evaporation level [%] |
|---------------------|----------------------|---------------------|----------------------|---------------------|----------------------|---------------------|----------------------|---------------------|
| 450                 | 2.5                  | 100                 | 3                    | 100                 | 3,5                  | 100                 | 4                    | 99,00               |
| 440                 | 2.5                  | 97,00               | 3                    | 91,00               | 3,5                  | 92,93               | 4                    | 92,00               |
| 430                 | 2.5                  | 90,00               | 3                    | 88,00               | 3,5                  | 78,79               | 4                    | 68,04               |
| 420                 | 2.5                  | 81,63               | 3                    | 66,33               | 3,5                  | 56,00               | 4                    | 64,00               |
| 410                 | 2.5                  | 81,63               | 3                    | 66,33               | 3,5                  | 56,00               | 4                    | 64,00               |

![Figure 11. Comparison between non- and equilibrium dryness fraction along virtual line (\( p_{inlet} = 4 \text{ bar} \) and \( T_{inlet} = 410 \text{ K} \)).](image)

The value of the critical inlet temperature which determine the border between total and partial evaporation on the shock wave depends on the pressure conditions, the purity of steam, position and shape of the shock wave, oscillation of the shock, level of the steam subcooling etc.. Additionally the calculation time for one set of the boundary conditions is very long. This causes that determination of this temperature is very time consuming.

### 5. Conclusions

The model of a single continuum with a special microstructure growing up during phase transitions was validated on a experiment carried out by Puzyrewski [4] on the planar symmetrical IMP PAN nozzle. The CFD results obtained by using our model agree very well with experiment data (pressure distribution along nozzle wall and full evaporation on the shock wave for V-th set of boundary conditions). Our numerical investigation has shown that:
- with decreasing value of the inlet temperature the evaporation level also decreases,
- the level of condensate evaporation on the shock wave depends on the boundary conditions, the purity of steam, localization and shape of the shock wave, oscillation of the shock, level of the steam subcooling, number of shocks in supersonic part of the nozzle, etc.,
- the evaporation level on normal shock is different with comparison with the evaporation level on oblique shocks,
- the position of the nucleation zone mostly depended on the inlet temperature and the purity of steam,
- precisely determination value of inlet temperature which determine the border between total and partial evaporation on the shock wave is very difficult.

References
[1] Kornet S and Badur J 2015 Trans. of IFFM 128 119-130
[2] Grzona A and Olivier H 2012 28th International Symposium on Shock Waves 2 141-146 (Springer Berlin Heidelberg)
[3] Weiss A and Olivier H 2014 Shock Waves 24 11–19
[4] Puzyrewski R, Gardzilewicz A and Bagińska M 1973 Archives of Mechanics 25 393-409
[5] Kornet S and Badur J 2015 3rd Polish Congress of Mechanics and 21st Computer Methods in Mechanics 2 523-524 (ed M Kleiber et al.)
[6] Bilicki Z and Badur J 2003 Journal of Non-Equilibrium Thermodynamics 28 145-172
[7] Namieśnik K and Dörffer P 2004 TASK Quarterly 9 53-63
[8] Bourgoing A and Reijasse Ph 2006 Shock Waves 24 251-258
[9] Sellam M et al 2014 Shock Wave 24 33-39
[10] Verma S B and Manisanka C 2014 Shock Wave 24 191-209
[11] Papamoschou D and Johnson A 2006 36th AIAA Fluid Dynamics Conference and Exhibit (San Francisco, California)
[12] Gawehn T et al 2010 Shock Waves 20 297–306
[13] Bourgoing A and Reijasse Ph 2005 Shock Waves 14(4) 251–258
[14] Papamoschou D, Zill A and Johnson A 2009 Shock Waves 19 171–183
[15] Badur J et al 2011 Proc. of microCAD “International Scientific Conference” (Miscolc)
[16] Banaszkiewicz M and Badur J 2000 TASK Quarterly 4 213-290
[17] Zakrzewski W, Karcz M and Kornet S 2012 Trans. of IFFM 124 111-124
[18] Chandler K, Melas M and Jorge T 2015 ASME Turbo Expo 2015: Turbine Technical Conference and Exposition (Montreal, Canada)