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1	CFD modeling of condensation process of water vapor in
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14	Abstract: The condensation phenomenon of vapor plays an important role in various
15	industries, such as the steam flow in turbines and refrigeration system. A
16	mathematical model is developed to predict the spontaneous condensing phenomenon
17	in the supersonic flows using the nucleation and droplet growth theories. The
18	numerical approach is validated with the experimental data, which shows a good
19	agreement between them. The condensation characteristics of water vapor in the
20	Laval nozzle are described in detail. The results show that the condensation process is
21	a rapid variation of the vapor-liquid phase change both in the space and in time. The
22	spontaneous condensation of water vapor will not appear immediately when the steam

reaches the saturation state. Instead, it occurs further downstream the nozzle throat,where the steam is in the state of supersaturation.

25

Keywords: condensation; water vapor; Laval nozzle; supersonic flow

26 **1. Introduction**

The condensation phenomenon of vapor plays an important role in various industries, such as the steam flow and water vapor in nozzles [1], turbines [2], ejectors [3], thermos-compressors [4] and supersonic separators [5-9]. Theoretical and experimental studies have been conducted for the condensation process in supersonic flows, focusing on the nucleation theory, droplet size, latent heat [10-12]. Numerical simulations have been performed to predict the condensing flow with the development of the computational fluid dynamics (CFD) for several decades.

34 Hill [13], Noori Rahim Abadi et al. [14] studied the nucleation process of wet steam flows in nozzles at low and high pressure, respectively. White & Young 35 predicted the condensing process using Eulerian-Lagrangian and time-marching 36 methods [15]. Gerber [16] developed the Eulerian-Lagrangian and Eulerian-Eulerian 37 two-phase models for predicting the condensation flow with the classical nucleation 38 theory. The effects of friction factor on the condensation flows in the Laval nozzles 39 40 were performed using the single fluid model by Mahpeykar & Teymourtash [17], and Jiang et al. [18]. Two-dimensional simulation of the condensing steam was calculated 41 in converging-diverging nozzles using a Jameson-style finite volume method on an 42 unstructured and adaptive triangular mesh [19]. Yang & Sheng [20] described a 43 conservative two-dimensional compressible numerical model for the non-equilibrium 44

condensing of the steam flow based on the classical nucleation theory and the Virial type equation of state. The effect of the expansion rate on the steam condensing flow through a converging-diverging nozzle was studied numerically by Nikkhahi et al. [21]. The steam condensing flow was modeled through the Laval nozzles at low and high inlet pressures by means of the single-fluid model [22]. The Eulerian-Eulerian approach was adopted for modeling the condensing steam flow, and the simulation was conducted on the commercial ANSYS FLUENT 12.1 platform [23].

The condensation phenomenon of water vapor in supersonic flows is still not 52 understood very well as a result of the complex phase change process. Especially, the 53 numerical simulation depends on various nucleation theories and droplet growth 54 models. In this paper, the Euler-Euler two-phase flow model is developed to predict 55 56 the spontaneous condensing phenomenon in the Laval nozzle. The modified internally consistent classic nucleation theory and Gyarmathy's droplet growth model are 57 employed to perform the simulation cases. The numerical approach is validated with 58 experimental data. The condensation process of water vapor is numerically analyzed 59 in detail, including the nucleation rate, droplet numbers, droplet radius and droplet 60 fraction. 61

62 **2. Mathematical model**

63 2.1. Governing equations

For the water vapor condensation in a Laval nozzle, the fluid flow is governed by partial differential equations describing the conservation of mass, momentum and energy, as shown in Eqs. (1-3).

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = S_m \tag{1}$$

83

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + S_{u_i}$$
(2)

69
$$\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial x_j}(\rho u_j H + p) = -\frac{\partial}{\partial x_j}(\lambda_{eff} \frac{\partial T}{\partial x_j}) + \frac{\partial}{\partial x_j}(u_i \tau_{ij}) + S_{h_i}$$
(3)

where ρ , u, p and H are the density, velocity, pressure and total enthalpy, respectively. λ_{eff} and T are the effective heat conductivity and temperature. The source terms, S_m , S_{u_i} , S_{h_i} , are needed in these equations to consider the effect of the condensation process.

Additionally, two transport equations are employed to describe the phase change process during the condensation of the water vapor. In this simulation, the conservation equations include the liquid fraction (Y) and droplet number (N), which can be given by:

78
$$\frac{\partial(\rho Y)}{\partial t} + \frac{\partial}{\partial x_j} \left(\rho Y u_j \right) = S_Y$$
(4)

79
$$\frac{\partial(\rho N)}{\partial t} + \frac{\partial}{\partial x_j} (\rho N u_j) = \rho J$$
(5)

where the source term S_Y describes the condensation rate of the water vapor, and J is the nucleation rate, respectively.

82 The source term can be defined as follows:

 $S_m = -S_Y = -\dot{m} \tag{6}$

$$S_{u_i} = -\dot{m}u_i \tag{7}$$

$$S_{h_i} = -\dot{m}h_i \tag{8}$$

$$\dot{m} = \frac{4\pi r^{*3}}{3} \rho_l J + 4\pi r^2 \rho_l N \frac{dr}{dt}$$
(9)

⁸⁷ where \dot{m} is the condensation mass per unit vapor volume per unit time. ρ_l is the ⁸⁸ droplet density, *r* is the droplet radius. dr/dt is the growth rate of droplets. The r^* is the ⁸⁹ Kelvin-Helmholtz critical droplet radius, which can be given by

90
$$r^* = \frac{2\sigma}{\rho_l R_v T \ln(S)}$$
(10)

where S is the super saturation ratio, defined as the ratio of vapor pressure to the
 equilibrium saturation pressure.

⁹³ The nucleation rate, *J*, can be calculated by the internally consistent classic
⁹⁴ nucleation theory (ICCT) [24], which predicts the nucleation process of the water
⁹⁵ vapor as follows:

96
$$J = \frac{\zeta}{S} \frac{\rho_v^2}{\rho_l} \sqrt{\frac{2\sigma}{\pi m_v^3}} \exp\left(-\frac{16\pi}{3} \frac{\sigma^3}{k_B^3 T_v^3 \rho_l^2 (\ln S)^2}\right) \exp(\Theta)$$
(11)

⁹⁷ where σ is the liquid surface tension, m_v is the mass of a vapor molecule, k_B is the ⁹⁸ Boltzmann's constant, T_v is the vapor temperature, ζ is a correction factor, Θ is a ⁹⁹ dimensionless surface tension.

100
$$\Theta = \frac{\sigma a_0}{k_B T_v}$$
(12)

¹⁰¹ where a_0 is the molecular surface area.

102 The growth rate of droplets due to evaporation and condensation, dr/dt, is 103 calculated by Gyarmathy's model by [25],

104
$$\frac{dr}{dt} = \frac{\lambda_{\nu} \left(T_s - T_{\nu}\right)}{\rho_l h} \frac{\left(1 - r^*/r\right)}{\left(r + \frac{\sqrt{8\pi}}{1.5 \operatorname{Pr}} \frac{\gamma}{\gamma + 1}l\right)}$$
(13)

105 where λ_{ν} is the heat conductivity coefficient of the vapor, *h* is the vapor specific 106 enthalpy, T_s is the saturated steam temperature, γ is the vapor adiabatic exponent, Pr is 107 the Prandtl number.

108 *2.2. Turbulence model*

Depending on the information required, different turbulence models can be applied for the numerical simulation of supersonic flows, from k- ε model [26-28], Shear Stress Turbulent (SST) k- ω [29], Large Eddy Simulation (LES) to Direct Numerical Simulation (DNS). In this paper, the k- ε turbulence model is used to predict the supersonic flows. The equations for the turbulence model are not documented here for brevity, but are however well documented elsewhere [30].

115 *2.3. Numerical schemes*

116 The commercial package ANSYS FLUENT 17 is employed as the computational platform. The conservation equations (1)-(3) for vapor phase are directly solved in 117 FLUENT, while the governing equations (4)-(13) for liquid phase and the source 118 terms are performed with C code by the User-Defined-Scalar (UDS) and 119 User-Defined-Function (UDF) interfaces. The SIMPLE algorithm [31] is used to 120 couple the velocity field and pressure. The second-order upwind scheme is adopted 121 for an accurate prediction. The transient state solution is used in the numerical studies 122 with a time step of 10^{-6} s. The inlet conditions for the nozzle entrance are chosen from 123 experimental tests including total pressure and total temperature. Since the flow is 124 supersonic at the nozzle outlet, the pressure at the outlet does not influence the 125 solution and is assigned an arbitrary low value. The convergence criterion for the 126

relative residual of the continuity and all other dependent variables is set to 10^{-3} and 10⁻⁶, respectively. The mass imbalance value is assigned as 10^{-4} to ensure iteration convergence.

130 **3. Results and discussion**

The validation, verification and implementation of the numerical studies are 131 conducted using the geometry and experimental data from the available literature by 132 Moses & Stein [12]. In their studies, the Laval nozzle was employed to 133 experimentally study the condensation process of water vapor in supersonic flows. 134 135 The nozzle throat is located at x=82.2 mm with the dimension of 10.0 mm (height) \times 10.0 mm (depth). A sketch of the geometry of the Laval nozzle used in the 136 experiments is described in Fig. 1. The subsonic part is composed of an arc with a 137 138 radius of 53.0 mm, while the transonic and supersonic parts consist of an arc with a radius of 686.0 mm. 139









The grid density is one of the key factors that determines the accuracy of the 143 numerical simulation. Three different densities of the structural grids are used to test 144 the grid independence, including the coarse (8640 cells), medium (23040 cells), fine 145 (51840 cells) and very fine (246400) grids. The static pressure and temperature at the 146 nozzle inlet for the simulations are 54702.17 Pa and 373.15 K, respectively. One of 147 the condensation parameters, the nucleation rate, is selected to evaluate the effect of 148 the grid density on the condensation simulation. The nucleation rate along the axis of 149 the Laval nozzle is shown in Fig. 2. We can see that the nucleation rate calculated 150 from the coarse grid significantly deviates from other cases, while the medium, fine 151 and very fine grids represent similar results. Therefore, the grid system with 23040 152 cells is used to conduct our simulations considering the computing accuracy and 153 154 efficiency.





Fi

Fig. 2 Effect of grid density on nucleation rate in supersonic flows

157 *3.2. Model validation*

The static pressure is firstly compared between the numerical and experimental 158 data at the inlet pressure of 54702.17 Pa and inlet temperature of 373.15 K. The 159 numerical result of the static pressure is shown in Fig. 3, and the value at the central 160 line is employed for the data validation. Fig. 4 depicts the dimensionless pressure, 161 defined as the ratio of local static pressure to the inlet one, along the central axis of 162 the Laval nozzle. We can see that the predicted onset of the condensation process at 163 x=104 mm, occurs earlier than the experimental test at x=107 mm. The increase of the 164 static pressure due to the condensing flow in the simulation is smaller than the 165 experiments. 166

167 Then, the droplet fraction due to the condensation process is employed to 168 validate the numerical model. The pressure and temperature at the nozzle inlet are 169 40050.04 Pa and 374.30 K, respectively. Fig. 5 shows the numerical and experimental 170 data of the droplet fraction along the axis in the Laval nozzle. The numerical model 171 predicts the droplet fraction in supersonic flows, although almost all of the numerical 172 results are less than the experimental data.

Generally, the numerical model is validated in detail by comparing the static pressure and droplet fraction during the condensation process in the Laval nozzle. The comparison results demonstrate that the numerical model can accurately capture the condensation process of the water vapor in the Laval nozzle.



Fig. 3 Numerical results of static pressure in the Laval nozzle





181

Fig. 4 Numerical and experimental results of static pressure at the central line of

the Laval nozzle



Fig. 5 Numerical and experimental results of droplet fraction at the central line of
the Laval nozzle

185 *3.3. Condensation process*

In this section, the condensation process of the water vapor is numerically 186 calculated in the above mentioned Laval nozzle at the inlet pressure of 54702.17 Pa 187 and temperature of 373.15 K, respectively. Fig. 6 shows the computational contours of 188 the Mach number in the Laval nozzle, and the detailed information at the center line is 189 described in Fig. 7. It can be observed that the vapor accelerates to a supersonic speed 190 191 and correspondingly results in the increase of the Mach number. However, the Mach number starts to decrease, when the spontaneous condensation of water vapor occurs. 192 This can be explained that the change of the latent heat between the phase transition 193 process from the vapor to liquid will heat the water vapor. After that, the steam 194 expands again, and the Mach number increases in the diverging part of the Laval 195 nozzle. 196



198

Fig. 6 Mach number contours in the Laval nozzle





200

Fig. 7 Mach number at the central line of the Laval nozzle

Figs. 8 and 9 show the degree of supercooling and nucleation rate during the water vapor condensation process. We can see that the supercooling degree increases constantly along with the vapor expansion, and it rapidly rises to the peak value of about 33 K in this case. In this condition, the steam is in an extremely non-equilibrium thermodynamic state, leading to the occurrence of the spontaneous condensation in a very short moment, which can be observed in Fig. 9. The degree of supercooling then suddenly decreases from 33 K to 2 K, which means that the 208 condensation process has finished.

Fig. 9 obviously reflects the nucleation process of water vapor in supersonic 209 flows. The nucleation process starts to occur approximately at x = 100 mm, and 210 sharply rises from 0 to 7.2×10^{21} m⁻³ s⁻¹ in a very short time. It means that a massive 211 212 number of condensation nuclei appear in the steam. In a short while, the nucleation rate drastically declines from peak to zero because of the decrease of the supercooling 213 degree. It indicates that the water vapor will not spontaneously condense at once when 214 the steam reaches the saturation state. On the contrary, the nucleation phenomenon 215 216 occurs somewhere downstream the nozzle throat, and shows a rapid variation both in space and in time. 217



218

219

Fig. 8 Degree of supercooling at the central line of the Laval nozzle





222

Fig. 9 Nucleation rate at the central line of the Laval nozzle

The distribution of the droplet numbers at the center line of the Laval nozzle is 223 224 shown in Fig. 10. The vapor molecules constantly collide with each other and coalesce, and continuingly produce the critical nucleus, when the spontaneous 225 condensation starts to occur. Under this thermodynamic condition, a large number of 226 227 droplets will appear when the condensation nucleus reaches a certain quantity and goes into the droplet growth process. The droplet numbers also rapidly rise from 0 to 228 1.12×10^{17} in a very short distance due to the sharp process of the vapor nucleation. 229 Then, the steam is almost back to the equilibrium state because of the decrease of the 230 supercooling degree. At that moment, no new condensation nucleui appear and the 231 droplet number remains effectively unchanged. 232







Fig. 10 Droplet numbers at the central line of the Laval nozzle

Figs. 11 and 12, respectively, show the radius and mass fraction of the droplet at 235 236 the center line of the Laval nozzle. The large numbers of vapor molecules are able to aggregate on the droplet surface, when the nucleation rate and droplet numbers reach 237 the peak. The radius and mass fraction of the droplet also begin to rapidly increase as 238 239 a result of the large number of the condensing nuclei and droplet numbers. It also can be seen that the increase of the droplet mass fraction lags behind the change of the 240 droplet radius by comparing Figs. 11 and 12. It means that the droplet radius changes 241 in the first place and then the droplet fraction grows dramatically. Combining Figs. 8 242 243 and 9, we also find that the vapor molecules can still continue to aggregate on the droplet surface due to the supercooling degree at about 2 K, when the droplet number 244 245 remains unchanged. Therefore, the radius and mass fraction of the droplet increase continuously till the nozzle outlet as a result of the state of supersaturation. 246





248

Fig. 11 Droplet radius at the central line of the Laval nozzle





Fig. 12 Droplet fraction of at the central line of the Laval nozzle

251 **4.** Conclusions

The condensation process of water vapor in the Laval nozzle is simulated numerically with the nucleation and droplet growth theories. The results show that the latent heat is released to heat into the vapor phase during the spontaneous condensation, leading to the jump of the condensing parameters. The degree of supercooling can reach a maximum value of about 33 K and correspondingly the spontaneous condensation occurs in a very short time. The droplet numbers also rapidly rise from 0 to 1.12×10^{17} in a very short moment. Then, the radius and mass fraction of the droplet also begin to increase continuously till the nozzle outlet as a result of the supercooling degree at about 2 K.

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267 **References**

- [1] S.J. Keisari, M. Shams, Shape optimization of nucleating wet-steam flow nozzle,
 Appl. Therm. Eng. 103 (2016) 812-820.
- [2] Y. Patel, G. Patel, T. Turunen-Saaresti, Influence of turbulence modelling on
 non-equilibrium condensing flows in nozzle and turbine cascade, Int. J. Heat
 Mass Transfer 88 (2015) 165-180.
- [3] N. Sharifi, M. Boroomand, M. Sharifi, Numerical assessment of steam nucleation
- on thermodynamic performance of steam ejectors, Appl. Therm. Eng. 52 (2013)
- **275 449-459**.

276	[4] S.M.A. Noori Rahim Abadi, R. Kouhikamali, K. Atashkari, Non-equilibrium
277	condensation of wet steam flow within high-pressure thermo-compressor, Appl.
278	Therm. Eng. 81 (2015) 74-82.
279	[5] C. Wen, A. Li, J.H. Walther, Y. Yang, Effect of swirling device on flow behavior in

- a supersonic separator for natural gas dehydration, Sep. Purif. Technol. 168 (2016)
 68-73.
- [6] C. Wen, Y. Yang, J.H. Walther, K.M. Pang, Y. Feng, Effect of delta wing on the
 particle flow in a novel gas supersonic separator, Powder Technol. 304 (2016)
 284 261-267.
- [7] Y. Yang, A. Li, C. Wen, Optimization of static vanes in a supersonic separator for
 gas purification, Fuel Process. Technol. 156 (2017) 265-270.
- [8] Y. Yang, C. Wen, CFD modeling of particle behavior in supersonic flows with
 strong swirls for gas separation, Sep. Purif. Technol. 174 (2017) 22-28.
- [9] Y. Yang, C. Wen, S. Wang, Y. Feng, P. Witt, The swirling flow structure in
 supersonic separators for natural gas dehydration, RSC Adv. 4 (2014)
 52967-52972.
- [10] S. Dykas, M. Majkut, M. Strozik, K. Smołka, Experimental study of condensing
 steam flow in nozzles and linear blade cascade, Int. J. Heat Mass Transfer 80
 (2015) 50-57.
- [11] H. Ding, C. Wang, Y. Zhao, An analytical method for Wilson point in nozzle flow
 with homogeneous nucleating, Int. J. Heat Mass Transfer 73 (2014) 586-594.
- [12] C. Moses, G. Stein, On the growth of steam droplets formed in a Laval nozzle

- using both static pressure and light scattering measurements, J. Fluids Eng. 100(1978) 311-322.
- 300 [13] P.G. Hill, Condensation of water vapour during supersonic expansion in nozzles,
- 301 J. Fluid Mech. 25 (1966) 593-620.
- 302 [14] S.M.A. Noori Rahim Abadi, R. Kouhikamali, K. Atashkari, Two-fluid model for
- simulation of supersonic flow of wet steam within high-pressure nozzles, Int. J.
 Therm. Sci. 96 (2015) 173-182.
- 305 [15] A. White, J. Young, Time-marching method for the prediction of
 306 two-dimensional, unsteadyflows of condensing steam, J. Propul. Power 9 (1993)
 307 579-587.
- 308 [16] A. Gerber, Two-phase Eulerian/Lagrangian model for nucleating steam flow, J.
 309 Fluids Eng. 124 (2002) 465-475.
- 310 [17] M.R. Mahpeykar, A. Taymourtash, The effects of friction factor and inlet
 311 stagnation conditions on the self condensation of steam in a supersonic nozzle,
 312 Sci. Iranica 11 (2004) 269-284.
- 313 [18] W. Jiang, Z. Liu, H. Liu, H. Pang, L. Bao, Influences of friction drag on
 314 spontaneous condensation in water vapor supersonic flows, Sci. China Ser. E:
- 315 Technol. Sci. 52 (2009) 2653-2659.
- 316 [19] D. Simpson, A. White, Viscous and unsteady flow calculations of condensing
 317 steam in nozzles, Int. J. Heat Fluid Flow 26 (2005) 71-79.
- 318 [20] Y. Yang, S. Shen, Numerical simulation on non-equilibrium spontaneous
 319 condensation in supersonic steam flow, Int. Commun. Heat Mass Transfer 36

(2009) 902-907. 320

- [21] B. Nikkhahi, M. Shams, M. Ziabasharhagh, A numerical study of two-phase 321
- transonic steam flow through convergence-divergence nozzles with different rates 322
- of expansion, Korean J. Chem. Eng. 27 (2010) 1646-1653. 323
- [22] S. Dykas, W. Wróblewski, Numerical modelling of steam condensing flow in low 324
- and high-pressure nozzles, Int. J. Heat Mass Transfer 55 (2012) 6191-6199. 325
- [23] A.H. Yousif, A.M. Al-Dabagh, R.C. Al-Zuhairy, Non-equilibrium spontaneous 326 condensation in transonic steam flow, Int. J. Therm. Sci. 68 (2013) 32-41. 327
- [24] S.L. Girshick, C.P. Chiu, Kinetic nucleation theory: A new expression for the rate 328
- of homogeneous nucleation from an ideal supersaturated vapor, J. Chem. Phys. 329 93 (1990) 1273-1277. 330
- [25] G. Gyarmathy, The spherical droplet in gaseous carrier streams: review and 331 synthesis, Multiphase Sci. Technol. 1 (1982) 99-279. 332
- [26] C. Wen, X. Cao, Y. Yang, Y. Feng, Prediction of mass flow rate in supersonic 333 natural gas processing, Oil Gas Sci. Technol. 70 (2015) 1101-1109. 334
- [27] C. Wen, X. Cao, Y. Yang, W. Li, An unconventional supersonic liquefied 335 technology for natural gas, Energy Educ. Sci. Technol. Part A Energy Sci. Res. 30 336 (2012) 651-660. 337
- [28] Y. Yang, C. Wen, S. Wang, Y. Feng, Numerical simulation of real gas flows in 338 natural gas supersonic separation processing, J. Nat. Gas Sci. Eng. 21 (2014)
- 829-836. 340

339

[29] Y. Yang, C. Wen, S. Wang, Y. Feng, Effect of Inlet and Outlet Flow Conditions on 341

- Natural Gas Parameters in Supersonic Separation Process, PloS One 9 (2014)
 e110313.
- [30] F.R. Menter, Two-equation eddy-viscosity turbulence models for engineering
 applications, AIAA J. 32 (1994) 1598-1605.
- 346 [31] S.V. Patankar, D.B. Spalding, A calculation procedure for heat, mass and
- 347 momentum transfer in three-dimensional parabolic flows, Int. J. Heat Mass
- 348 Transfer 15 (1972) 1787-1806.