INVESTIGATION OF UNSTEADY TWO-PHASE FLOW OF WET STEAM THROUGH NOZZLES

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ABSTRACT

A numerical model for the solution of unsteady one-dimensional two-phase flow of wet steam accompanied with spontaneous condensation in supersonic nozzles is described. The effect of introducing the coefficient β, which is a correction for nucleation work of nucleation rate, is taken into account. The effect of condensation coefficient α_c is also presented. Comparisons between predictions of the suggested method and experimental results of both the present experiments and published ones and also between other theoretical works were also made there. The comparisons show satisfactory agreement.

Keywords : Spontaneous condensation, nucleation, supersonic nozzle, unsteady flow, and vapour subcooling.

INTRODUCTION

Problems of multiphase flow appear recently in many areas of technology and energy production. Two-phase flow of wet steam in the last stages of steam turbines, of both conventional and nuclear power plants, has been considered as one of the greatest importance of these problems. The wet steam flow, was found to be affected mainly with the so called "condensation coefficient". Condensation coefficient is defining the fraction of the impinging vapour molecules which adhere to the surface of water droplets suspended inside wet steam medium.

In view of earliest measurements of this coefficient, Sherwood and Johannes [1] obtained different values for the condensation coefficient of condensed liquids and concluded that all liquids did not have condensation coefficients equal unity. Young [2] has suggested recently that the condensation coefficient has similar values for wet steam flows under equilibrium conditions (i.e., when the condensation rate is zero), whilst it has different values when non-equilibrium condition prevails and consequently a net condensation effect occurs. Therefore, it is common to take the value of the condensation coefficient equal unity in the most of the numerical models, which treat nucleation and condensation processes [2,3]. Gajewski *et al.* [4] have presented a theoretical approach which considers variable values for both the condensation and evaporation coefficients during non-equilibrium condensation processes of water vapour.

In simulating and solving many of the condensation problems, such as shock waves and losses, good agreement between measurements and predictions of condensation theories must be achieved. This agreement was confirmed by utilizing different values for the condensation and evaporation coefficients as in [5] and [6]. It is of great importance to note that Hill [5] and Soltanov *et al.* [6] used random values for these coefficients. At present, Mahmoud [7] revised most of the published data on the condensation and evaporation coefficients in a numerical procedure in order to conjoin these coefficients with the pressure value at Wilson point in free molecular, intermediate and continuum flow regimes. He showed that the condensation coefficient depends significantly upon the pressure at Wilson point, vapour subcooling,

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droplet size, evaporation coefficient and index of isentropic expansion.

The present work verifies a theoretical model, based on one dimensional, unsteady two-phase flow approximations, to simulate the spontaneous condensation during steam expansion through supersonic nozzles. The proposed model utilizes the suggested formulation of the condensation coefficient in Reference 7 and selected values for the coefficient β, in the nucleation rate equation, to acquire satisfactory agreement between pressure measurements, from literature or present experiments through nucleation and condensation zones, and present predictions. Furthermore, a detailed analysis for the effect of both the condensation coefficient α_c and correction coefficient β on the condensation characteristics, such as nucleation rate, vapour subcooling and droplet size are also enclosed in the present work.

THEORETICAL TREATMENT

Phase Description and Phase Transformation

The general characteristics of adiabatic, spontaneous condensation, unsteady one-dimensional steam flow through supersonic nozzles are described below under the following assumptions:

- i- Vapour density is low enough, so that it is considered thermally perfect.
- ii- Water-phase consists of monodispresed incompressible spherical droplets.
- iii- Initial flow condition corresponds to the single-phase condition or wet steam condition.
- iv- Mechanism of water-phase formation is generally the spontaneous formation (i.e., homogeneous nucleation) of water nuclei from the pure vapour at sufficiently high supersaturation.
- v- Water droplet is so small enough, that the vapour and water phases are in dynamic equilibrium.
- vi- The initial flow properties of steam may be expressed as follows [8]:

$$T_s = 273 + 10 \times \left(\frac{p}{9.81}\right)^{1/4}$$

$$\sigma = 0.132 - 0.207 \times 0.001 \times T_s$$

$$\varsigma = (762.4 - 0.6 \times T_s) \times 4.19$$

Flow Equations

With the above assumptions, a set of unsteady equations governing the mass, momentum and energy transfer in the steam flow along the flow element shown in Figure 1 are presented below. The basic equations were illustrated previously by Danelen [8].

Continuity equation of vapour phase:

$$\frac{\partial \rho_1 A}{\partial t} + \frac{\partial \rho_1 c A}{\partial z} = -\chi \cdot A \tag{1}$$

Momentum equation for vapour phas

$$\frac{\partial \rho_1 c A}{\partial t} + \frac{\partial (\rho_1 c^2 + p) \cdot A}{\partial z} = -c \cdot \chi \cdot A + p \frac{\partial A}{\partial z} \tag{2}$$

The unsteady equation for the energy conservation of the vapour phase contained in the flow element of Figure 1 is expressed by:

$$\rho_1 \frac{\partial i_{o1}}{\partial t} + \rho_1 c \frac{\partial i_{o1}}{\partial z} = \frac{\partial p}{\partial t} + \chi \cdot (i_1 - \mu_f) \tag{3}$$

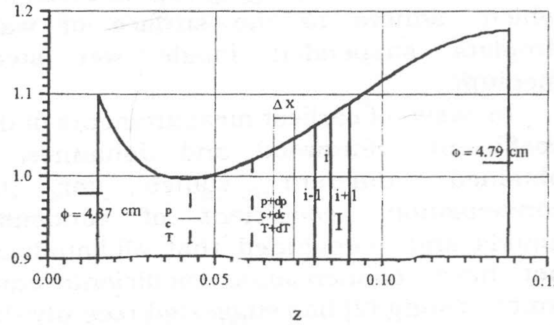


Figure 1 Profile of nozzle and flow element.

Here, i_{o1} is the stagnation enthalpy of the vapour phase, μ_f is the Gibbs function of the substance undergoing phase conversions. For the case considered, μ_f is defined as:

$$\mu_r = i_1 - T_1 \cdot S_1 \qquad (4)$$

While the density distribution of condensed phase (droplet) with respect to its size in one-dimensional flow is as follows:

$$\frac{\partial \|N\| A}{\partial t} + \frac{\partial \|N\| c A}{\partial z} = -J \cdot A \qquad (5)$$

$$\frac{\partial \|N\| \langle r_d \rangle A}{\partial t} + \frac{\partial \|N\| c \langle r_d \rangle A}{\partial z} = A(J \cdot r_* + a_2 \|N\|) \qquad (6)$$

$$\frac{\partial \|N\| \langle r_d^2 \rangle A}{\partial t} + \frac{\partial \|N\| c \langle r_d^2 \rangle A}{\partial z} = A(J \cdot r_*^2 + 2 \cdot a_2 \|N\| \langle r_d \rangle) \qquad (7)$$

Where,

$$\|N\| = \int N(r) \cdot dr \qquad (8)$$

$$\langle r_d^2 \rangle = \int f(r) \cdot r^2 \cdot dr \qquad (9)$$

$$f(r) = \frac{N(r)}{\|N\|} \qquad (10)$$

Where, N(r) is the non-normalizing density distribution of droplet.

Supplementary Equations

The system of Equations 1 to 3 for the vapour phase and 5 to 7 for the condensed phase may be extended by the following equations:

a- Thermal equations of state used in Reference 12 are:

$$p_1 = \rho_1 \cdot R_B \cdot T_1, \quad \text{Where, } R_B = B.R \qquad (11)$$

$$i_1 = \frac{\gamma}{(\gamma - 1)} \cdot \frac{p_1}{\rho_1} + \text{const.} \qquad (12)$$

b- An equation for the vapour entropy is:

$$S_1 = S_{in} + \frac{R_B}{(\gamma - 1)} \ell n[\frac{p_1}{p_{in}} (\frac{\rho_{in}}{\rho_1})^{\gamma}] \qquad (13)$$

c- The Kelvin-Helmhaltz relation, describing the radius of a critical droplet in meta-stable equilibrium with a supercooled vapour is:

$$r_* = \frac{2 \cdot \sigma_2 \cdot T_s}{\rho_2 \cdot \varsigma \cdot \Delta T_s} \qquad (14)$$

d- An equation for nucleation J is [6]:

$$J = (\frac{p_1}{kT_1})^2 \cdot v_m \cdot \sqrt{\frac{2 \cdot \sigma_2 \cdot m_o}{\pi}} \cdot \text{Exp}(-\beta \frac{\Delta w(r_*)}{kT_1}) \qquad (15)$$

Where,

Δw (r_*) is the nucleation work and is determined as in Reference 6 by the formula:

$$\Delta w(r_*) = \frac{4}{3} \pi \cdot r_*^2 \cdot \sigma_2 \qquad (16)$$

e- The rate of phase conversion (mass flux of condensed phase) χ may be expressed as follows based on the equation of density distribution of droplet [8,9]:

$$\chi = \int N(r) \cdot \frac{dm(r)}{dt} \cdot dr \qquad (17)$$

Where $\frac{dm(r)}{dt}$ is the mass velocity change of droplet, which can be expressed by the following relation:

$$\frac{dm(r)}{dt} = \frac{4\pi p r_d^2 \alpha_c}{\sqrt{2\pi R_B T_1}} \cdot (1 - \sqrt{\frac{T_1}{T_2}}) \qquad (18)$$

By inserting Equations 8, 9, 10 and 18 in Equation 17 then,

$$\chi = \bar{a} \cdot [\|N\| \cdot \langle r_d^2 \rangle, \qquad (19)$$

Where, $\bar{a} = \frac{4\pi p \alpha_c}{\sqrt{2\pi R_B T_1}} \cdot (1 - \sqrt{\frac{T_1}{T_2}})$

Method of solution

With reference to the typical arrangement shown in Figure 1, the channel was divided into a number of $\Delta x = L/n$ where, n is the number of steps.

The system of Equations 1 to 3 and also 5 to 7 can be integrated with respect to time using the finite difference technique [11], under the following conditions:

Inlet conditions

$t = 0 \quad , \quad x \in [0, L],$

$p = p_{in} \quad , \quad \rho = \rho_{in} \quad$ and $\quad c = c_{in}$

Exit conditions

$x = L$ and $p = p_2$

Boundary conditions

The index i and i +1 are the boundary of I th cell as shown in Fig. (2). The quantities at the boundary of cell I can be calculated as follows:

$$a = \frac{1}{2}\sqrt{\gamma \cdot (p_{I-1} + p_I) \cdot (\rho_{I-1} + \rho_I)}$$

$$\tilde{p} = \frac{1}{2}[p_{I-1} + p_I \cdot a \cdot (c_{I-1} - c_I)]$$

$$u = \frac{1}{2}[c_{I-1} + c_I + (\frac{p_{I-1} - p_I}{a})]$$

$$\rho^l = \frac{(\gamma + 1)\tilde{p} + (\gamma - 1)p_{I-1}}{(\gamma - 1)\tilde{p} + (\gamma + 1)p_{I-1}} \cdot \rho_{I-1}$$

$$\rho^r = \frac{(\gamma + 1)\tilde{p} + (\gamma - 1)p_I}{(\gamma - 1)\tilde{p} + (\gamma + 1)p_I} \cdot \rho_I$$

$$D^l = c_{I-1} - \frac{a}{\rho_{I-1}}$$

$$D^r = c_I + \frac{a}{\rho_I}$$

Under the following conditions:

D^l and D^r are both positive

$c_i = c_{I-1} \quad , \quad p_i = p_{I-1} \quad$ and $\quad \rho_i = \rho_{I-1}$

D^l and D^r are both negative

$c_i = c_I \quad , \quad p_i = p_I \quad$ and $\quad \rho_i = \rho_I$

D^l and D^r are negative and $u > 0.0$

$c_i = u \quad , \quad p_i = \tilde{p}$ and $\quad \rho_i = \rho^l$

$c_i = u \quad , \quad p_i = \tilde{p} \quad$ and $\quad \rho_i = \rho^r$

The time step Δt is calculated from the condition:

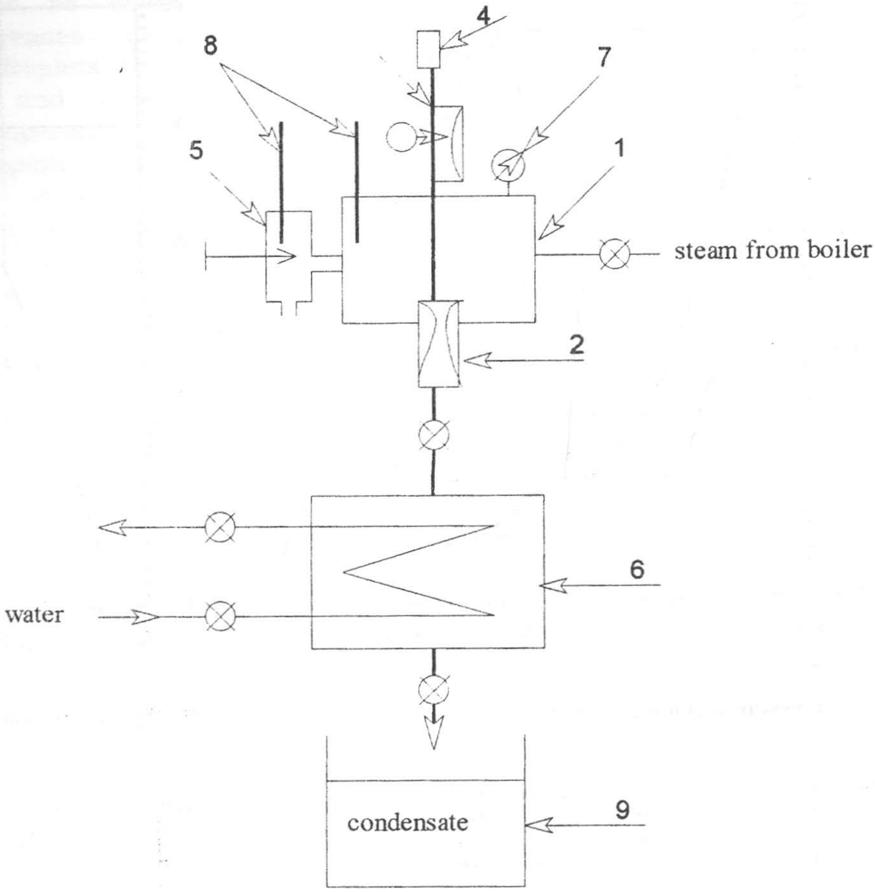
$$\Delta t < \frac{\Delta x}{q} \qquad \text{where,}$$

$$q = \max. [|D^l|;|D^r|]$$

EXPERIMENTAL APPARATUS AND MEASURING DEVICE

A schematic diagram of the experimental set-up is shown in Figure 2. It consists of a steam vessel (1), which is fed with wet steam from a fire-tube boiler of one ton/hour capacity at a maximum pressure of 6 bar. The investigated nozzle (2) was made from brass and manufactured with the profile shown in Figure1. The tested nozzle is screwed into the bottom of the steam vessel and is supplied with steam from this vessel. Exhaust steam is condensed in a surface condenser (6) and is rated in a metering tank.

Measurements of the static pressure distribution along the nozzle axis, steam flow rate, static vapour temperature, and the wetness fraction by the throttling calorimeter (5) at the nozzle inlet were carried out. The axial pressure variation along the nozzle axis was measured with the aid of a Stodola search tube (3) of nominal diameter of 3.31 mm. The Stodola search tube was equipped with a pressure transducer (4). The probe is traversed in increments of 2.5 mm by rotating a calibrated dial (D). The vapour velocity at the nozzle inlet was obtained by measuring the steam flow rate, vapour pressure and temperature inside the vessel. A mercury-in-glass thermometer (8) was used to obtain the static temperature of the wet steam flow in the vicinity of the nozzle inlet inside the steam vessel. Furthermore, a pressure gauge (7) was used to indicate the vessel steam pressure. The steam vessel is connected to a throttling calorimeter (5) with a mercury in glass thermometer (8) and a pressure gauge in order to identify the steam wetness ahead of nozzle entrance.

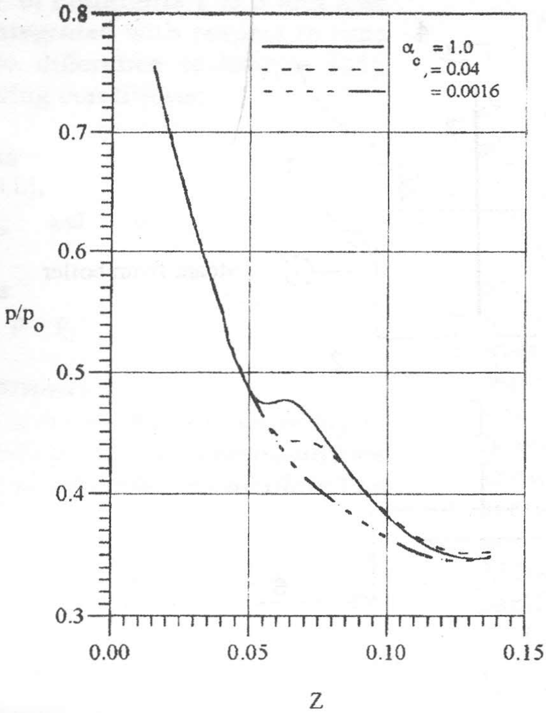


1- steam vessel
2- nozzle
3- search tube
4- pressure transducer
5- throttling calorimeter
6- surface condenser
7- pressure gauge
8- thermometer
9- metering tank

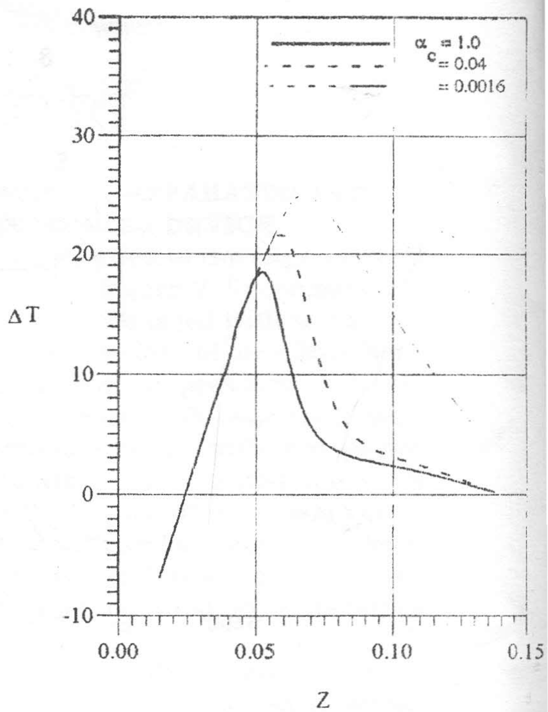
Figure 2 Schematic diagram for the experimental setup

RESULTS AND DISCUSSION

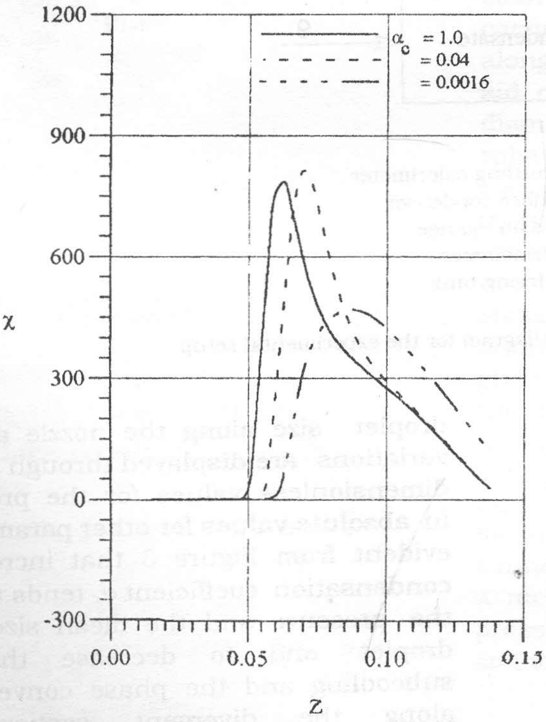
The predictions, presented herein are obtained for the nozzle profile, shown in Figure 1. These predictions illustrate the effects of changing the initial pressure, condensation coefficient α_c and the coefficient β on the two-phase flow characteristics. The boundary conditions are stated with these predictions. Figure 3 presents the effect of changing α_c on the variation of the axial pressure, vapour subcooling, phase conversion rate and mean droplet size along the nozzle axis. These variations are displayed through Figure 3 in dimensionless values for the pressure and in absolute values for other parameters. It is evident from Figure 3 that increasing the condensation coefficient α_c tends to increase the pressure and the mean size of water droplet and to decrease the vapour subcooling and the phase conversion rate along the divergent section of the investigated nozzle.



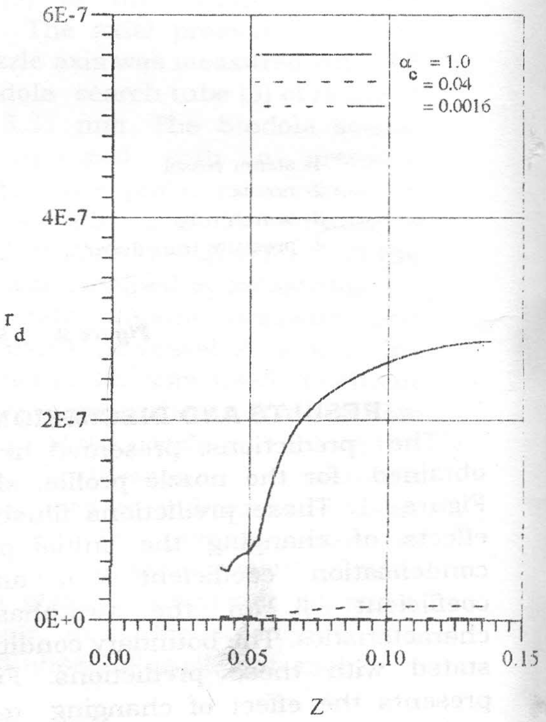
a- pressure variation along nozzle axis.



b- vapour subcooling along nozzle axis.



c- phase conversion rate along nozzle axis.



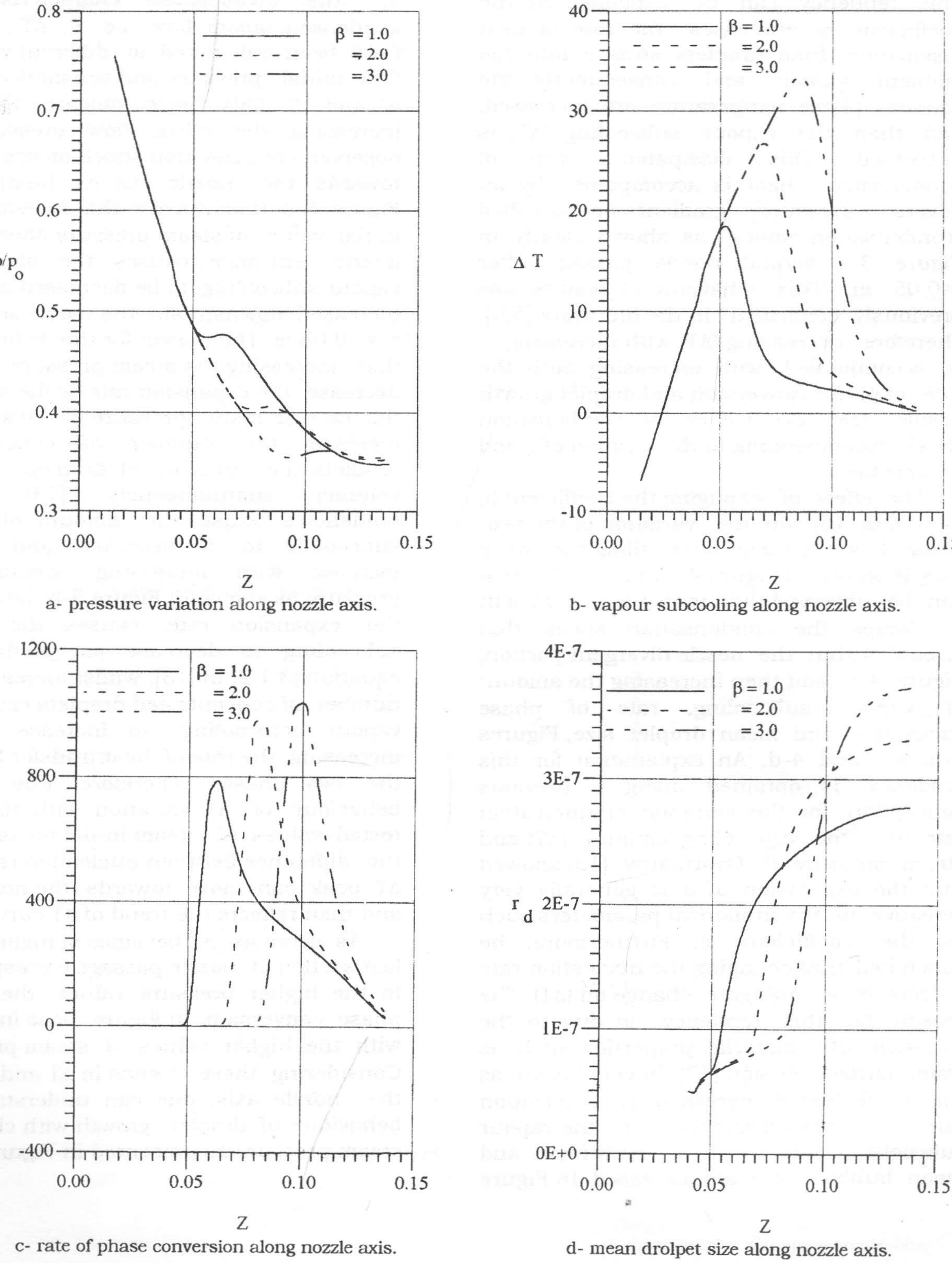
d- mean droplet size along nozzle axis.

Figure 3 Effect of changing the condensation coefficient (α_c) on the flow characteristics at constant values of p_o =6.83 bar, β=1.0 & ΔT_i =3 K

This tendency can be explained as the coefficient α_c increases the rate of heat dissipation from droplets surface into the ambient vapour and consequently the vapour phase temperature are increased, and then the vapour subcooling (ΔT) is decreased. This dissipated rate of condensation heat is accompanied by an adverse pressure gradient or so-called "condensation shock" as shown clearly in Figure 3-a behind nozzle passage after z=0.05 m. This behaviour of results was previously confirmed in the literature [5,6]. Therefore, decreasing (ΔT) with increasing α_c is accompanied with increasing both the rate of phase conversion and droplet growth beside the occurrence of condensation shock corresponding to the location of χ and r_d increase.

The effect of changing the coefficient β, (Equation 15), on the variation of the two-phase flow characteristics along the nozzle axis is shown in Figure 4. From this figure it can be observed that, increasing coefficient β damps the condensation shock that formed within the nozzle divergent portion, Figure 4-a and then increasing the amount of vapour subcooling, rate of phase conversion and mean droplet size, Figures 4-b, 4-c and 4-d. An explanation for this tendency is obtained using a previous conception for the variation of nucleation rate with the subcooling amount (ΔT) and steam pressure P. Gyarmathy [13] showed that the expression of J is generally very sensitive to the numerical parameters such as the coefficient β. Furthermore, he concluded that changing the nucleation rate reflects in a conjugate change on (ΔT). The reason for this tendency is due to the variation of material properties such as water surface tension [13]. In conclusion, as the coefficient β increases the nucleation rate J is decreased and therefore, the vapour subcoolig, rate of phase conversion and mean bubbles size are increased. In Figure 5, the investigated characteristics of condensed steam flow; i.e. P, ΔT , χ and r_d have been calculated at different values of flow initial pressure and constant values of α_c and β. This figure indicates that with increasing the initial flow pressure, the observed condensation shock moves forward towards the nozzle exit as illustrated in Figure 5-a. It shows also that increasing the initial value of steam pressure ahead of the nozzle entrance causes the amount of vapour subcooling to be decreased and then increased downstream the nozzle section at z = 0.05 m. The reason for this behaviour is that increasing the steam pressure tends to decrease the expansion rate or the so-called the rate of static pressure decrease and to increase the number of concentrated droplets (i.e., number of droplets per unit volume) simultaneously [13]. These tendencies cause the amount of vapour subcooling to be decreased and then to increase with increasing steam initial pressure as shown in Figure 5-b. Decreasing the expansion rate, causes the vapour subcooling to decrease as predicted by equation (3.1.2) in [13], whilst increasing the number of concentrated droplets causes the vapour subcooling to increase due to increasing the rate of heat transfer between the two phases. Therefore, due to the behaviour of ΔT variation with the three tested values of steam initial pressure and the difference between nucleation rates; the ΔT peak can move towards the nozzle exit and then reflects the trend of ΔT curves.

As soon as ΔT becomes of higher in the last section of nozzle passage corresponding to the higher pressure values, the rate of phase conversion in Figure 5-c is increased with the higher values of steam pressure. Considering these trends in ΔT and χ along the nozzle axis, one can understand the behaviour of droplet growth with changing steam pressure as presented in Figure 5-d.



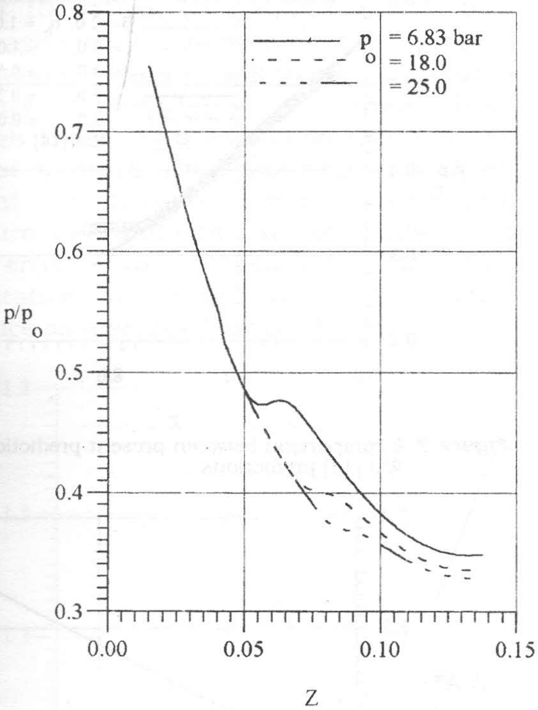
a- pressure variation along nozzle axis.

b- vapour subcooling along nozzle axis.

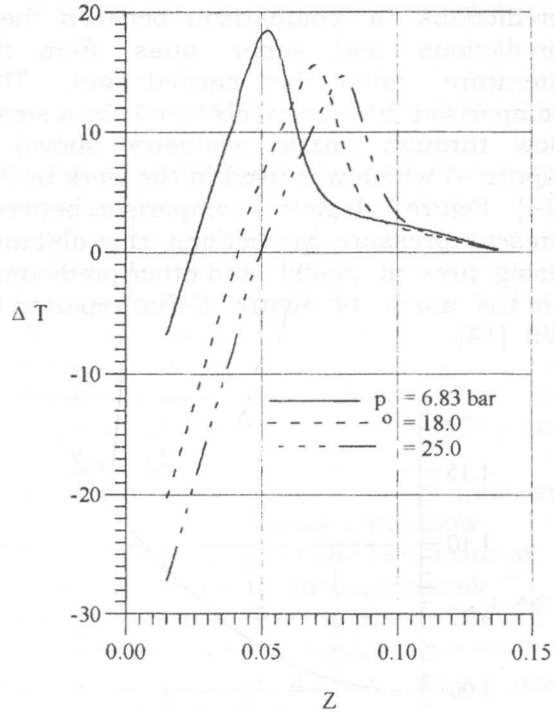
c- rate of phase conversion along nozzle axis.

d- mean drolpet size along nozzle axis.

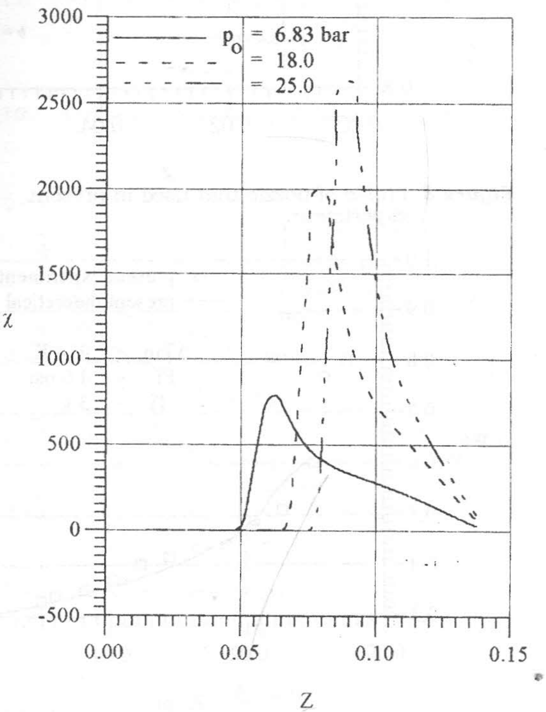
Figure 4 Effect of changing the coefficient (β) on the flow characteristics at constant values of p_o =6.83 bar, α_c =1.0 & ΔT_i =3 K



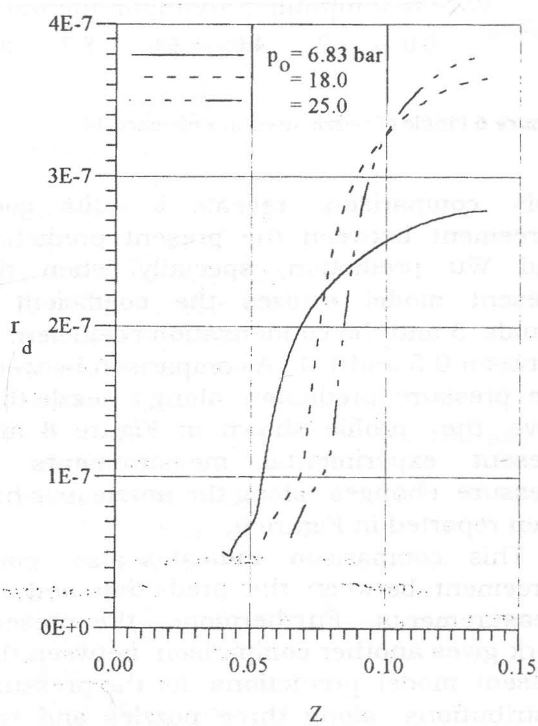
a- pressure variation along nozzle axis.



b- vapour subcooling along nozzle axis.



c- phase conversion rate along nozzle axis.



d- mean droplet size along nozzle axis.

Figure 5 Effect of changing the initial pressure on the flow characteristics at constant values of α_c=1.0, β=1.0 & ΔT_i=3 K.

In order to confirm the present predictions, a comparison between these predictions and other ones from the literature must be carried out. This comparison has been obtained for a steam flow through nozzle geometry shown in Figure 6 which was used in the work by Wu [14]. Figure 7 depicts a comparison between present pressure predictions that obtained using present model and other predictions on the nozzle of Figure 6 that reported by Wu. [14].

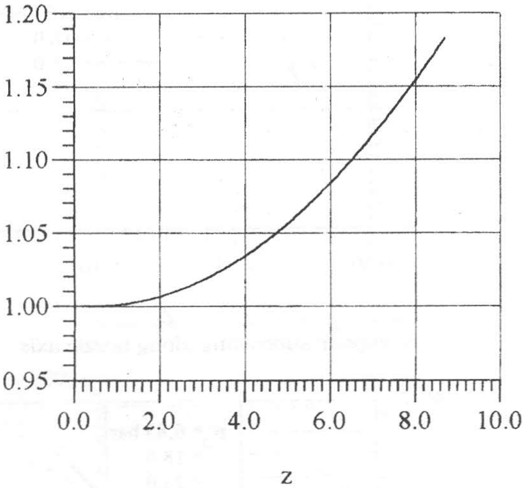


Figure 6 Profile of nozzle used in Reference 14.

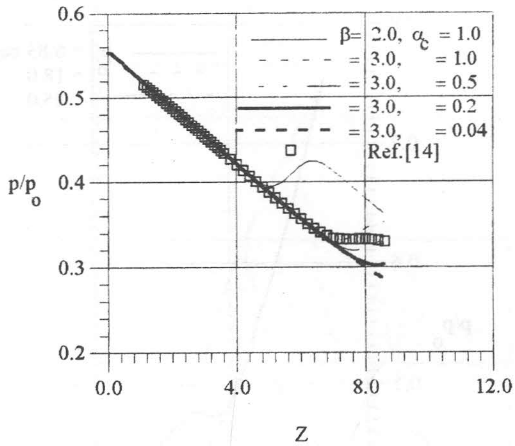


Figure 7 A comparison between present predictions and Wu [14] predictions.

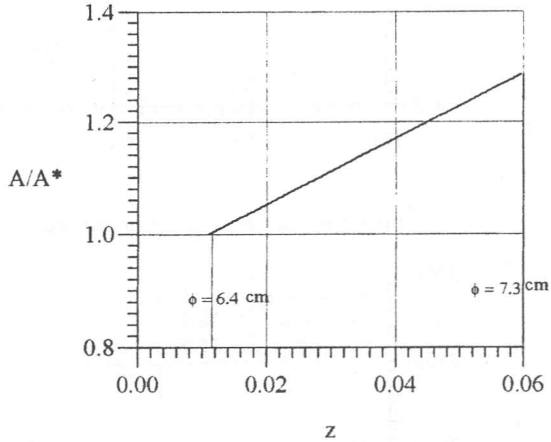


Figure 8 Profile of nozzle that used in present experiment.

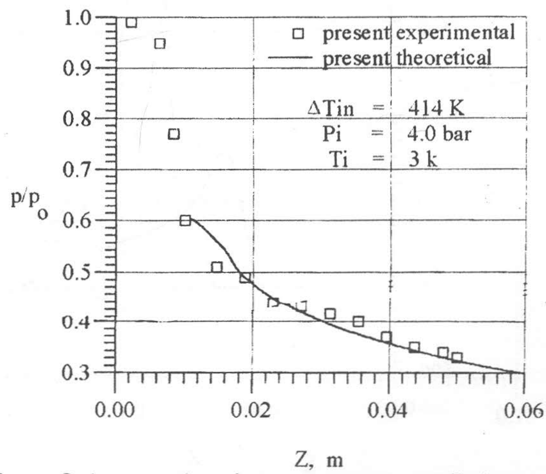


Figure 9 A comparison between present predictions and present experiments of pressure variation along nozzle (3)

This comparison reveals a quite good agreement between the present prediction and Wu prediction, specially when the present model utilizes the coefficient β equals 3 and the condensation coefficient α_c between 0.5 and 1.0. A comparison between the pressure prediction along a nozzle that have the profile shown in Figure 8 and present experimental measurements of pressure changes along the nozzle axis has been reported in Figure 9.

This comparison indicates also good agreement between the prediction and the measurements. Furthermore, the present work gives another comparison between the present model predictions for the pressure distributions along three nozzles and the measured values of these distributions that have been reported by Bakhtar [15].

Profiles of these nozzles are illustrated in Figure 10. It can be seen in Figure 11 that the agreement between the present predictions and Bakhtar's measured pressure distributions of steam flows through these nozzles is good except in the case of nozzle L. The disagreement between present predictions and experimental pressure distributions can be attributed to the errors in measuring the inlet temperature of steam ahead the nozzle entrance as discussed by Bakhtar [15].

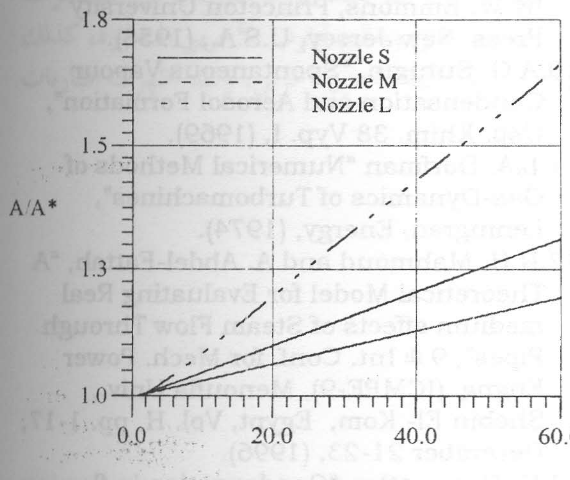


Figure 10 Profiles of nozzles S, M & L from Reference 15

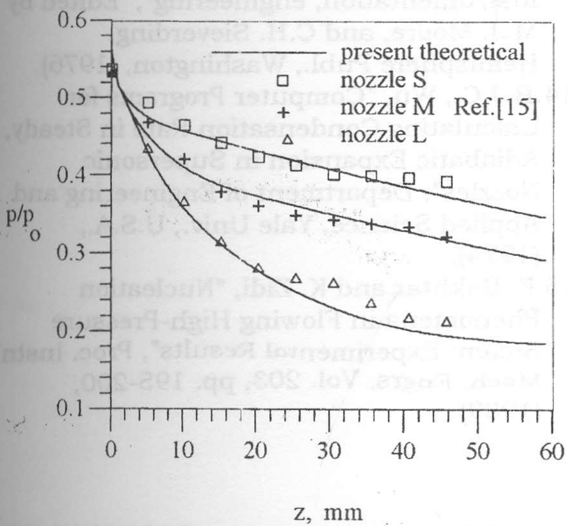


Figure 11 Comparison between present predictions and measured values of pressure variation along nozzles by Reference 5.

CONCLUSIONS

The present results may be summarized as follows:

1- Increasing the condensation coefficient only in the theoretical model suppresses both the subcooling (ΔT) and the rate of phase conversion, while rises the flow pressure and mean radius of the condensed water droplets.
2- Increasing the coefficient β, while keeping the other parameters constant, results in the damping of the pressure gradient along the nozzle passage and consequently increasing the condensation parameters, i.e., (ΔT); χ and r_d, of wet steam flow.
3- Increasing the steam flow initial pressure, as a sample of changing initial flow parameters, can affect the behaviour of steam condensation through nozzle.
4- Comparison between the present model predictions, based on selected values for the coefficients α_c and β, and predictions of other investigators and present measurements showed good agreement.

NOMENCLATURE

A: nozzle area; m^2
B: compressibility;
c: velocity; $m.s^{-1}$
D: simplifying symbol;
e: internal energy; $kJ.kg^{-1}$
i: enthalpy; $kJ.kg^{-1}$
J: nucleation rate; s^{-1}
k: Boltzman constant; $J.K^{-1}$
L: nozzle length; m
m: droplet mass; kg
m_o: molecular weight; $mol.kg^{-1}$
N: non-normalizing density distribution of droplet;
p: pressure; bar
r_d: droplet radius; m
r_*: critical dimension of nucleus; m
R: gas constant; $kJ.\ kg^{-1}.K^{-1}$
S: entropy; $kJ.\ kg^{-1}.K^{-1}$
t: time; s
T: absolute temperature; K^{-1}
v_m: volume per one molecule in a condensed phase; $m^3.mol.^{-1}$
u: simplifying symbol;
z: distance along nozzle axis; m

α_c: condensation coefficient;
β: correction factor for nucleation work;
γ: specific hear ratio;
σ: surface tension coefficient; $N.m^{-1}$
ρ: density; $kg.m^{-3}$
μ: Gibbs function; $kJ.\ kg^{-1}$
ς : latent heat of evaporation; $kJ.\ kg^{-1}$
χ: phase conversion rate; $kg.m^{-3}.s^{-1}$
Δw: nucleation work; N.m

Subscripts

1: vapour phase;
2: water phase;
*: critical;
c: condensed;
d: droplet;
0: stagnation;
s: saturation;

Superscripts

l: left;
r: right;

REFERENCES

1. T.K.Sherwood, and C. Johannes, "The Maximum Rate of Sublimation of Solids", J.A.I.Ch.E., Vol. 8, pp. 590, (1962).
2. J.B. Young, "The Spontaneous Condensation of Steam in Super-Sonic Nozzles", Physico-Chemical Hydrodynamics, Vol. 3, pp. 57-82, (1982).
3. F. Bakhtar, and K. Zidi, "Nucleation Phenomena in Flowing High-Pressure Steam", Proc. Inst. Mech. Engrs., Vol. 204, pp. 233-242, (1990)
4. P. Gajewski, A. Kulicki, A. Wisniewski, and M. Zgorzelshi, " Kinetic Theory Approach to the Vapour-Phase Phenomena in a Non-Equilibrium Condensation Process", Phys. Fluids, Vol. 17, No. 2, pp. 321-327, (1974).
5. P.G. Hill, " Condensation of Water Vapour During Supersonic Expansion in Nozzles", J. Fluid Mech., Vol. 25, Part 3, pp. 593-620, (1966).
6. G.A. Soltanov, L. I. Seleznev, and G. V. Tsiklauri, "Generation and Growth of Condensed Phase in High-Velocity Flows", Int. J. Heat Mass Transfer, Vol. 16, pp. 1577-1587, (1973).
7. N.H. Mahmoud, "Condensation Coefficient and Wetness Thermal Losses of Wet Steam Flow at Low Pressures", 8 th Int. Conf. for Mech. Power Engng. (ICMPE-8), Alexandria Univ., Alexandria, Egypt, Vol. 3, pp. 221-236, April 27-29, (1993).
8. V.C. Danelen, J.V. Tsiklauri, and L.I. Seleznev, "Adiabatic two-Phase Flow", Moscow; Atom Publishers, (1973).
9. H. Stiver "A condensation phenomenon in High-Velocity Flows", Chapter 3 in "Fundamentals of Gas Dynamics", Edited by W. Emmons, Princeton University Press, New Jersey, U.S.A., (1958).
10. A.G. Sutugin, "Spontaneous Vapour Condensation and Aerosol Formation", Usp. Khim. 38 Vyp. I, (1969).
11. L.A. Dorfman "Numerical Methods of Gas-Dynamics of Turbomachines", Leningrad, Energy, (1974).
12. N.H. Mahmoud and A. Abdel-Fattah, "A Theoretical Model for Evaluating Real medium effects of Steam Flow Through Pipes", 9 th Int. Conf. for Mech. Power Engng. (ICMPE-9), Menoufia Univ., Shebin El- Kom, Egypt, Vol. H, pp. 1-17, December 21-23, (1996).
13. G. Gyarmathy, "Condensation in flowing steam", Chapter (3) in "Two-Phase Steam Flow in Turbines and Separators :theory, instrumentation, engineering", Edited by M.J. Moore, and C.H. Sieverding, Hemisphere Publ., Washington, (1976).
14. B.J.C., Wu, "Computer Programs for Calculating Condensation Rate in Steady, Adiabatic Expansion in Supersonic Nozzles", Department of Engineering and Applied Science, Yale Univ., U.S.A., (1974).
15. F. Bakhtar and K. Zidi, "Nucleation Phenomena in Flowing High-Pressure Steam: Experimental Results", Proc. Instn Mech. Engrs, Vol. 203, pp. 195-200, (1989).

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فحص السريان ثنائى الطور الغير مستقر للبخار الرطب خلال الأبواق

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ملخص ا لبحث

تصف هذه الورقة نموذجا نظريا لحل السريان الأحادي البعد غير المستقر للبخار الرطب بالتكثف التلقائى (اللحظـــى) خلال أبواق فوق صوتيه، بأخذ النموذج فى الاعتبار إدخال تأثير المعامل β وهو معامل تصحيح لشغل تكوين الأنوية فى أس معادلة معدل تكون الأنوبة، كذلك بأخذ النموذج الرياضى فى الاعتبار تأثير معامل لتكثيف α_c. كما تعقد الورقة مقارنات بين التنبـــؤات المأخوذة من النموذج المقترح هنا ونتائج القياسات المعملية لكل من تجارب البحث الحالى ونتائج تجارب الآخرين المنشورة، كذلك فان الورقة تقدم مقارنات أخرى بين النتائج النظرية للنموذج المقترح ونتائج نظرية سابقة لباحثين آخرين، ولقد أظهرت المقارنات توافقا مقبولا.