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Entropy generation minimization in film condensation on a flat plate with interfacial shear stress

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Abstract
This study focuses on the second law analysis of film condensation on a flat plate. Based on the interfacial shear and the gravitational forces applied to the liquid film, two limiting cases are investigated. Finally, a general expression for total entropy generation is derived as a function of liquid film thickness and the effects of the two forces on total entropy generation rate are discussed. Using entropy generation minimization method (EGM), the existence of an optimum condition for each case is discussed.
Keywords: entropy generation minimization, second law analysis, film condensation, interfacial shear

Introduction
The importance of film condensation on a flat plate is due to its great number of industrial applications such as heat exchangers and condensers. Several condensing systems, such as flat plates, circular cylinders, spheres, and non-circular cylinders have been extensively studied regarding the phase-change heat transfer problem of film-wise condensation from the first law point of view.
Nusselt [1] first presented the basis for the problem of condensation and analyzed the local balance of viscous forces and the weight of the condensate. He showed that heat transfer in condensation depends on local film thickness. Following his work, many researchers have worked in this field [2-4]. The approaches have been along the same broad general lines, but since they use different assumptions and approximations, are of varying degrees of complexity. As for the effects of interfacial shear forces on condensation, Yang and Hsu [5] developed a simple mathematical model for the study of mixed convection film condensation with downward flowing vapors onto a horizontal elliptical tube. Koh et al. [6] obtained an exact boundary layer solution, while the shear forces at the liquid-vapor interface were taken into account. Shekriladze and Gomelaury [7] analyzed the problem assuming that the shear stress at the liquid vapor interface is equal to the loss of momentum of the condensing vapor. Dhir and Linhard [8] presented a similar solution for laminar film condensation on a two-dimensional isothermal surface. Churchill [9] investigated the effects of the inertia and the heat capacity of the condensate on the vapor drag and the curvature of the surface. Hsu and Yang [10] and Rose [11] modified the Shekriladze and Gomelauri model and took into account the pressure gradient effect by using the potential flow theory. Using perturbation methods, Mendez et al. [12] studied the conjugate heat transfer condensation process of standard vapor and the effect of longitudinal heat conduction on the thermal thick wall regime is taken into account.
The growing need for higher quality performance in thermal engineering systems have proposed the second law analysis as a great tool in improving such systems. Entropy generation is associated with thermodynamic irreversibility which is an inevitable phenomenon in all types of thermal processes. The two common sources of irreversibility in thermal systems are thermal irreversibility due to the finite temperature differences in thermal contacts and frictional irreversibility due to the viscous effects of the fluid.
Bejan [13] pioneered the method of entropy generation minimization (EGM) in various configuration and flow regimes. In his book [14], he also conducted the second law analysis of thermodynamics via the minimization of entropy generation for the single phase convection heat transfer. Later, Sahin [15] investigated the effect of temperature-dependant viscosity on the entropy generation rate as well as the ratio of pumping power to heat transfer. More recently, Jani et. al. [16] provided optimization of falling film LiBr solution on a horizontal single tube based on the minimization of entropy generation that irreversibility of non-isothermal heat transfer dominates in comparison with the fluid flow friction and mass transfer. Saouli and Aiboudi-Saouli [17] performed second law analysis of laminar liquid falling film along an inclined heated plate and found that fluid friction irreversibility dominates over heat transfer irreversibility. All the researchers mentioned above concentrated on the second law analysis of single-phase convection heat transfer problems.
As for phase-change thermal analysis, Naterer [18,19] applied heat-entropy analogies to problems involving phase change heat transfer with fluid flow, so that new physical insight and numerical error indicators (Adeyinka, Naterer [20]) could be gained from such entropy analysis. Their numerical and experimental results indicate that entropy can serve as an effective variable in describing and predicting various interfacial processes during phase change. Esfahani and Ziaei-Rad

[21] investigated an analysis of laminar film condensation on a vertical plate. They developed the work of Sparrow and Gregg focusing on more details using dimensionless equations and parameters. Adeyinka and Naterer [22] investigated the physical significance of entropy generation in plate film condensation. Using some simplification, optimum conditions for high interfacial shear is introduced. They observed that entropy generation provides a useful parameter in the optimization of a two-phase system. Dung and Yang [23] used the EGM technique to conduct the second law analysis in a saturated vapor flowing slowly onto and condensing on an isothermal horizontal tube and obtained an optimal diameter that generates a minimum of entropy generation at a given duty. Li and Yang [24] derived an expression for entropy generation number and performed an entropy generation minimization analysis in order to give an idea of optimal design on free convection film condensation on an elliptical cylinder. Yang et. al. [25] extended this work by performing the same analysis on a non-isothermal elliptical tube and compared their results with the previous work. Tzeng and Yang [26] also investigated a similar analysis on entropy generation optimization for film condensation on a sphere. They derived an expression for entropy generation number and performed an entropy generation minimization analysis in order to introduce an optimal diameter for laminar film condensation on a sphere. Haseli et. al. [27] investigated a numerical study of the entropy production of condensation of vapor in the presence of non-condensable gas in a counter current baffled shell and one-pass tube condenser. Their resultant profiles during the condensation process showed that a higher air mass flow rate leads to a lower rate of entropy production. They [28] also evaluated the optimum cooling water temperature during condensation of saturated water vapor within a shell and tube condenser, through minimization of exergy destruction.

In the present work, the entropy generation minimization of condensation on a flat plate is developed by focusing on more mathematical details than the previous studies [21,22]. Two limiting cases are introduced regarding the definition of boundary layer thickness: condensation on a flat plate with respect to gravitational forces and condensation on a horizontal plate with high interfacial shear forces. A general relation for total entropy generation as a function of boundary layer thickness is derived. Using entropy generation minimization method, the effects of interfacial shear and gravitational forces on entropy generation and the existence of an optimum condition is discussed for both cases.

Governing equations

The physical model and coordinate system under consideration are shown in Fig.1. A saturated pure vapor with a temperature of T_{sat} flows on an iso-thermal flat plate and imposes an interfacial shear (τ) which is supposed to be constant over the whole interfacial length. The wall temperature T_w is uniform and below the saturation temperature. Thus, condensation occurs on the wall and a continues liquid film runs over the plate under the combined effects of gravity and the vapor interfacial shear force. For a laminar, steady state condensate film with constant fluid properties, the boundary layer equations governed by the basis of conservation principles: mass, momentum, and energy are:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\mu\frac{\partial^2 u}{\partial y^2}=-g_x\left(\rho-\rho_v\right) \tag{2}$$

Energy:

$$k\frac{\partial^2 T}{\partial y^2}=0 \tag{3}$$

The momentum equation, Eq.2, reflects a balance of viscous and gravitational effects through the first and the second terms, respectively.

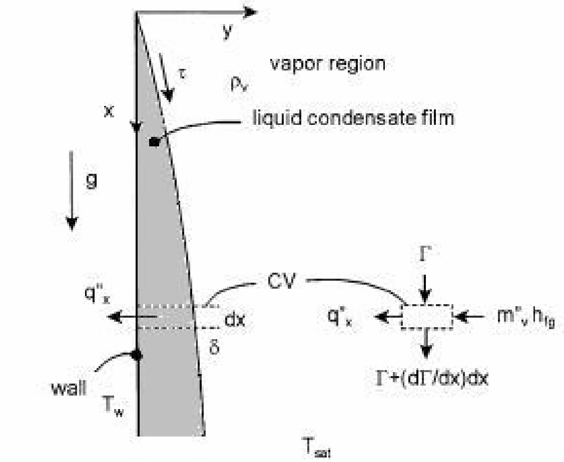

Fig.1 Physical model and coordinate system for condensate film flow on a flat surface

The boundary conditions subjected to the above equations are:

$$y=0,\qquad u=0;\qquad\qquad y=\delta,\qquad \mu\frac{\partial u}{\partial y}=\tau \tag{4}$$

$$y=0,\qquad T=T_w;\qquad\qquad y=\delta,\qquad T=T_{sat} \tag{5}$$

Note that when $\tau=0$ the problem is simplified to the classical theory of Nusselt for condensation. Applying the boundary conditions to the governing equations will result in the temperature and velocity profiles as below:

$$\frac{T-T_w}{T_{sat}-T_w}=\frac{y}{\delta} \tag{6}$$

$$u=\frac{g(\rho-\rho_v)\delta^2}{\mu}\left(\frac{y}{\delta}-\frac{1}{2}\frac{y^2}{\delta^2}\right)+\frac{\tau}{\mu}y \tag{7}$$

introducing a shear velocity as:

$$V_{shear}=\left(\frac{\tau}{\rho}\right)^{1/2} \tag{8}$$

Equation 7 can be rewritten as:

$$u = \frac{g(\rho - \rho_v)\delta^2}{\mu}\left(\frac{y}{\delta} - \frac{1}{2}\frac{y^2}{\delta^2}\right) + \frac{V_{shear}^2}{\upsilon} y \quad (9)$$

A balance of energy between the latent heat released at the interface through condensation and heat flux conducted through the condensate film to the wall surface leads to an additional equation for liquid film thickness:

$$\dot{m}_v'' h_{fg} = k\frac{\partial T}{\partial y} = k\frac{\Delta T}{\delta} \quad (10)$$

where $\dot{m}_v''$ is the condensate liquid mass rate and can be calculated using continuity equation (see Fig.1):

$$\dot{m}_v'' = \frac{\partial \Gamma}{\partial x} = \frac{\partial}{\partial x}\int_{y=0}^{y=\delta} \rho u dy \quad (11)$$

where Γ is the liquid mass rate. Substituting Eq.11 in Eq.10 and replacing the velocity profile from Eq.9 will result in the following equation for the liquid film thickness (δ):

$$\delta^3(1 + B\delta) = Ax \quad (12)$$

where *A* and *B* are constant values that are defined as below:

$$A = \frac{3k\upsilon\Delta T}{\dot{m} h_{fg}} = \frac{3k\upsilon\Delta T}{\rho V_{shear}^2 h_{fg}} \quad (13)$$

$$B = \frac{3}{4}\frac{g(\rho - \rho_v)}{\tau} = \frac{3}{4}\frac{g(\rho - \rho_v)}{\rho V_{shear}^2} \quad (14)$$

Note that the expression for *B* can be counted as a relation between the gravitational and interfacial shear forces.

Entropy generation rate

Local entropy generation at each point of flow field is introduced by Bejan [14] as:

$$\dot{P}_S'' = \frac{k}{T^2}\left(\frac{\partial T}{\partial y}\right)^2 + \frac{\mu}{T}\left(\frac{\partial u}{\partial y}\right)^2 \quad (15)$$

The first right term is the thermal entropy generation due to the finite temperature differences in thermal contacts and the second one is the frictional entropy generation due to the viscous effects of the fluid. Applying the velocity and temperature gradients to the above equation will lead to the frictional ($\dot{P}_{S,V}''$) and thermal ($\dot{P}_{S,T}''$) entropy generation rates as:

$$\dot{P}_{S,T}'' = \frac{K}{T_w^2}\left(\frac{\Delta T}{\delta}\right)^2 \frac{1}{\left(1 + \frac{\Delta T}{T_w}\frac{y}{\delta}\right)^2} \quad (16)$$

$$\dot{P}_{S,V}'' = \frac{\mu}{T_w}\frac{1}{\left(1 + \frac{\Delta T}{\delta} y\right)}\left(\frac{g(\rho - \rho_v)\delta}{\mu}\left(1 - \frac{y}{\delta}\right) + \frac{\tau}{\mu}\right)^2 \quad (17)$$

where

$$\Delta T = T_{sat} - T_W$$

Note that *T* in Eq.15 is substituted by the local temperature.

Integrating Eqs. 16 and 17 over the liquid film thickness will lead to the frictional ($\dot{P}_{S,V}'$) and thermal ($\dot{P}_{S,T}'$) entropy generation rates, respectively:

$$\dot{P}_{S,T}' = \int_{y=0}^{y=\delta} \dot{P}_{S,T}'' dy = A_{-1}\delta^{-1} \quad (18)$$

$$\dot{P}_{S,V}' = \int_{y=0}^{y=\delta} \dot{P}_{S,V}'' dy = A_1\delta^1 + A_2\delta^2 + A_3\delta^3 \quad (19)$$

where

$$A_{-1} = \frac{k(\Delta T)^2}{T_w T_{Sat}} \quad (20)$$

$$A_i = \frac{\tau^2}{\mu T_w} A_i' \left(\frac{g\Delta\rho}{\tau}\right)^{i-1}, \quad i = 1,2,3 \quad (21)$$

where A_i' are functions of $\varepsilon = \frac{\Delta T}{T_W}$ as below:

$$A_1' = 1 - \frac{\varepsilon}{2} + \frac{\varepsilon^2}{3} + \ldots$$
$$A_2' = 1 - \frac{\varepsilon}{3} + \frac{5\varepsilon^2}{12} + \ldots \quad (22)$$
$$A_3' = \frac{1}{3}\left(1 - \frac{\varepsilon}{4} + \frac{\varepsilon^2}{10} + \ldots\right)$$

Equations 18 and 19 show that as the boundary layer thickness (δ) increases, thermal entropy generation decreases and the frictional entropy generation increases which is physically acceptable. Integrating equations 18 and 19 on the whole plate length in x direction will lead to the thermal and frictional entropy generations, respectively. The total thermal entropy generations is defined as below:

$$\dot{P}_{S,T} = \int_{x=0}^{x=L} = \frac{3}{2}\frac{A_{-1}}{A}\delta_L^2(1 + \frac{8}{9}B\delta_L) \quad (23)$$

By introducing the total heat flux over the plate length as:

$$q' = \int_{x=0}^{x=L} q_x'' dx = \int_{x=0}^{x=L} \frac{k\Delta T}{\delta} dx = \frac{3}{2}\frac{k\Delta T}{\delta_L}\frac{1 + B\delta_L}{1 + \frac{8}{9}B\delta_L} L \quad (24)$$

Equation 23 can be rewritten in terms of the heat flux (q'):

$$\dot{P}_{S,T} = \frac{2}{3}(1 + \varepsilon)\frac{1}{k}\left(\frac{q'}{T_w}\right)^2 \frac{\delta_L}{L}\frac{1 + B\delta_L}{1 + \frac{8}{9}B\delta_L} \quad (25)$$

The total frictional entropy generations is also defined as:

$$\dot{P}_{S,V} = \frac{3}{4}\frac{\tau^2}{\mu T_W}\frac{\delta^4}{A}\left\{C_1' + C_2'\left(\frac{g\Delta\rho}{\tau}\delta\right) + C_3'\left(\frac{g\Delta\rho}{\tau}\delta\right)^2 + C_4'\left(\frac{g\Delta\rho}{\tau}\delta\right)^3\right\} \quad (26)$$

where

$$C'_1 = A'_1$$
$$C'_2 = \frac{4}{5}(A'_1 + A'_2)$$
$$C'_3 = \frac{2}{3}(A'_2 + A'_3) \qquad (27)$$
$$C'_4 = \frac{4}{7}A'_3$$

Similar to the previous calculations A'_i are functions of $\varepsilon = \frac{\Delta T}{T_W}$ (see Eq.14).

Entropy generation minimization

Equations 25 and 26 are the general expressions for the thermal and frictional entropy generation, respectively, with respect to the liquid film thickness which can be derived from Eq.12. However, due to the complexity of the problem in the general form, at this stage of the calculations, two limit cases are considered:

Case 1: $B\delta >> 1$

For high values of B, Eq.12 can be simplified to:

$$\delta^3(\mathrm{B}\delta) = \mathrm{Ax} \qquad (28)$$

and thus the film thickness will be defined as:

$$\frac{\delta_g}{L} = \frac{1}{L}\left(\frac{\mathrm{Ax}}{\mathrm{B}}\right)^{1/4} = \left(\frac{4K\upsilon\Delta T}{g\Delta\rho h_{fg}L^3}\right)^{1/4} = \left(\frac{4Ja}{Ra}\right)^{1/4} \qquad (29)$$

where

$$Ja = \frac{C_p\left(T_{sat} - T_w\right)}{h_{fg}} \qquad (30)$$

$$Ra_L = \frac{g\Delta\rho L^3}{\mu\alpha} \qquad (31)$$

This case can be considered as film condensation on a flat plate without interfacial shear force. Substituting δ in Eqs. 25 and 26 by Eq.29, relative equation for entropy generation becomes:

$$\dot{P}_S = B_V\lambda^3 + B_T\lambda^{-1} \qquad (32)$$

where

$$B_V = \frac{4}{21}\left(1 - \frac{\varepsilon}{4} + \frac{\varepsilon^2}{10}\right)\frac{\mu}{T_W}\left(\frac{g\Delta\rho L^2}{\mu}\right)^2 \qquad (33)$$

$$B_T = \frac{4}{3}K\frac{\varepsilon^2}{1+\varepsilon}$$

$$\varepsilon = \frac{\Delta T}{T_w}$$

$$\lambda = \left(\frac{4Ja}{Ra}\right)^{1/4} \qquad (34)$$

Equation 32 has an optimum point which can be obtained by $\partial\dot{P}_S/\partial\lambda = 0$:

$$\lambda_{opt} = \frac{1.1456A_\varepsilon q'}{\left(KT_{sat}/\mu\right)^{1/2} g\Delta\rho L^2} \qquad (35)$$

where

$$A_\varepsilon = \left(1 - \frac{\varepsilon}{2} + \frac{\varepsilon^2}{10}\right)^{-1/2} \qquad (36)$$

Note that $A_\varepsilon \to 1$ when $\varepsilon \to 0$. The optimum entropy generation is:

$$\dot{P}_{S,opt} = 4B_V\lambda_{opt}^3 = \frac{4}{3}B_T\lambda_{opt}^{-1} \qquad (37)$$

and the dimensionless number of entropy generation, N_S, will be defined as:

$$N_S = \frac{\dot{P}_S}{\dot{P}_{S,opt}} = \underbrace{\frac{3}{4}\frac{\lambda_{opt}}{\lambda}}_{N_{S,T}} + \underbrace{\frac{1}{4}\frac{\lambda^3}{\lambda_{opt}^3}}_{N_{S,F}} \qquad (38)$$

Case 2: $B\delta << 1$

For low values of B, Eq.12 can be simplified to:

$$\delta^3(1) = \mathrm{Ax} \qquad (۳9)$$

and thus the film thickness will be defined as:

$$\frac{\delta_\tau}{L} = \frac{1}{L}(\mathrm{Ax})^{1/3} = \left(\frac{3K\nu\Delta T}{\rho V_{shear}^2 h_{fg}L^2}\right)^{1/3} = \left(\frac{3Ja}{\mathrm{Pr}}\right)^{1/3}\mathrm{Re}_L^{-2/3} \qquad (40)$$

where

$$\mathrm{Re}_L = \frac{V_{shear}L}{\upsilon} = \left(\frac{\tau}{\rho}\right)^{1/2}\frac{L}{\upsilon} \qquad (41)$$

This case can be considered as film condensation on flat plate with interfacial shear force. Relative equation for entropy generation becomes:

$$\dot{P}_S = B_V\lambda^5 + B_T\lambda^{-1} \qquad (42)$$

where

$$B_V = \frac{3}{4}\frac{k\mu\upsilon^2}{L^2T_W}\left(1 - \frac{\varepsilon}{2} + \frac{\varepsilon^2}{3}\right)\left(\frac{3Ja}{\mathrm{Pr}}\right)^{\frac{1}{3}} \qquad (43)$$

$$B_T = \frac{2}{3k(1+\varepsilon)}\left(\frac{q'}{T_W}\right)^2\left(\frac{3Ja}{\mathrm{Pr}}\right)^{\frac{1}{3}}$$

$$\lambda = \left(\frac{\tau L^2}{\rho\upsilon^2}\right)^{1/3} \qquad (44)$$

Similar to Eq.35, the optimum entropy generation is obtained as:

$$\lambda_{opt} = \frac{0.562A_\varepsilon\left(q'/k\right)^{2/3}}{\left(\mu\tau T_{sat}\right)^{1/3}} \qquad (45)$$

where

$$A_\tau = \left(1 - \frac{\varepsilon}{2} + \frac{\varepsilon^2}{3}\right)^{-1/3} \tag{46}$$

The optimum entropy generation is:

$$\dot{P}_{S,opt} = 6B_V \lambda_{opt}^5 = \frac{6}{5} B_T \lambda_{opt}^{-1} \tag{47}$$

and the dimensionless number of entropy generation will be defined as:

$$N_S = \frac{\dot{P}_S}{\dot{P}_{S,opt}} = \underbrace{\frac{5}{6}\frac{\lambda_{opt}}{\lambda}}_{N_{S,T}} + \underbrace{\frac{1}{6}\frac{\lambda^5}{\lambda_{opt}^5}}_{N_{S,F}} \tag{48}$$

Results and discussion

Figure 2 indicates the non-dimensional liquid film thickness versus the non-dimensional plate length. As it is seen, the shear stress on the liquid-vapor interface will decrease the thickness of the liquid film.

The variation of thermal ($N_{S,T}$) and frictional ($N_{S,F}$) entropy generation numbers versus λ/λ_{opt} for the two cases of condensation with and without interfacial shear force are shown in Fig.3 (Equations 38 and 48). As it is expected, marching in the x direction will cause a decrease in the thermal entropy generation number which is due to the increase in the liquid film thickness and the resulting decrease in the temperature gradients. However, due to higher friction area, the frictional entropy generation increases with the increase in λ/λ_{opt} . As it may be noticed, for the case of condensation without interfacial shear stress, the frictional entropy generation is lower than the case of having interfacial shear stress which is expected due to the higher frictional irreversibility of the second case. As for the thermal entropy generation, the values of thermal entropy generation numbers for both cases are almost the same which is due to the same temperature profiles resulting in the same thermal gradients in the liquid film.

Figure 4 shows the variation of entropy generation number with λ/λ_{opt} . As it is seen, a minimum value exists for N_S which corresponds to an optimum value of λ for both cases: vertical plate with no shear and horizontal plate with shear. As it is shown, at low values of λ/λ_{opt} which corresponds to low values of plate length, frictional entropy generation number is low but the higher temperature difference needed to transfer the given q' for that surface area leads to higher values of thermal entropy generation. At high values of λ/λ_{opt} , the frictional entropy generation is higher than the thermal entropy generation due to the higher surface area of fluid friction compared to lower temperature difference between the wall and the surrounding fluid resulted by that surface area. Reverse results are recognized for higher values of λ/λ_{opt} .

The effect of interfacial shear stress on entropy generation ratio ($\Phi(x) = \dot{P}''_{S,V} / \dot{P}''_{S,T}$) is illustrated in Fig.5. It is shown that higher values of interfacial shear stress will cause an increase in the value of the entropy generation ratio. This is expected due to the increase in the frictional entropy generation discussed above.

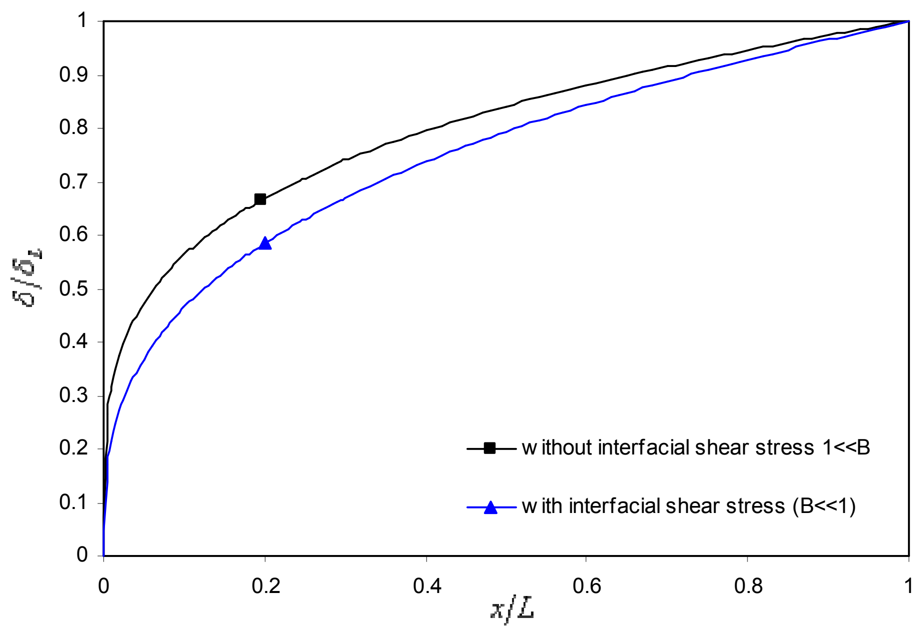

Fig.2 The effect of interfacial shear stress on film thickness

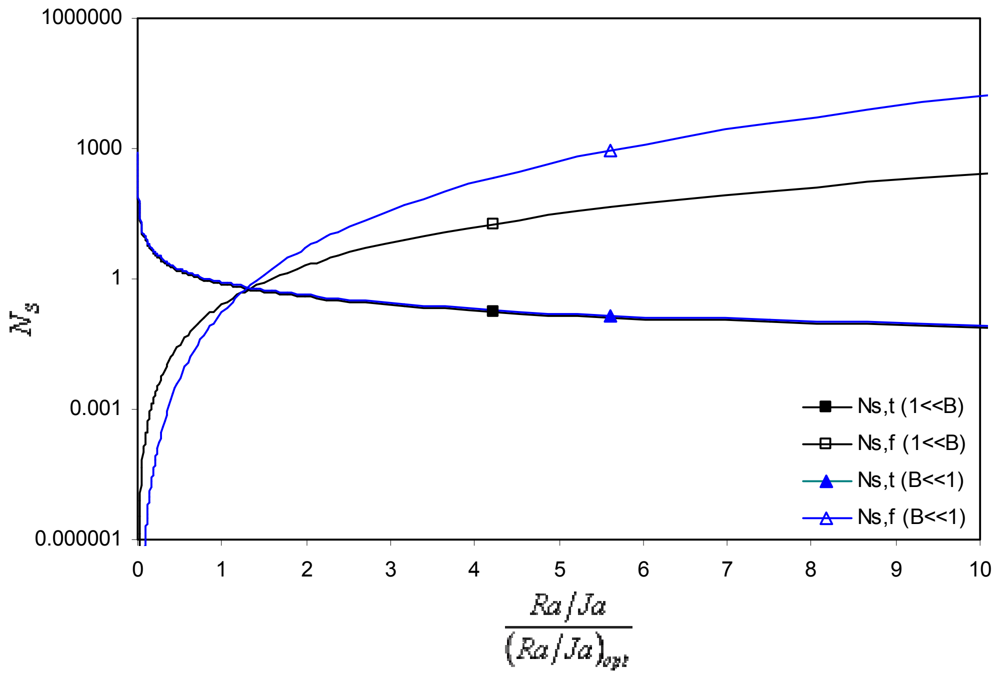

Fig.3 Comparison of thermal ($N_{S,T}$) and frictional ($N_{S,F}$) entropy generation numbers for both cases: condensation with interfacial shear force (*B<<1*) and condensation without interfacial shear force (*1<<B*)

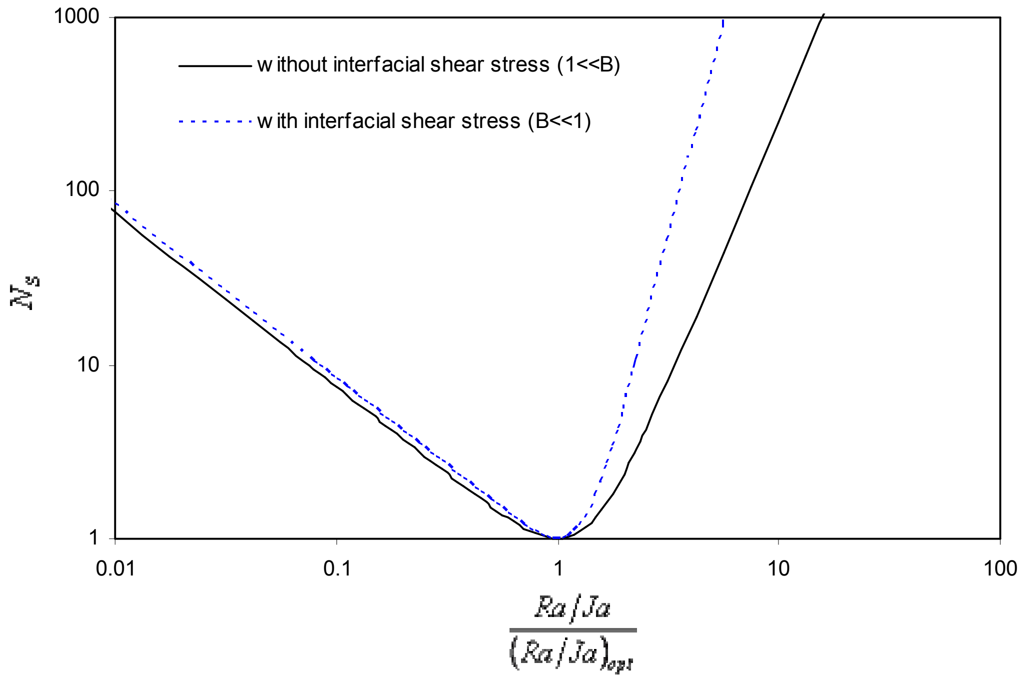

Fig.4 The variation of dimensionless entropy generation numbers versus $\frac{Ra/Ja}{(Ra/Ja)_{Opt}}$ for both cases: condensation with interfacial shear force (*B<<1*) and condensation without interfacial shear force (*1<<B*)

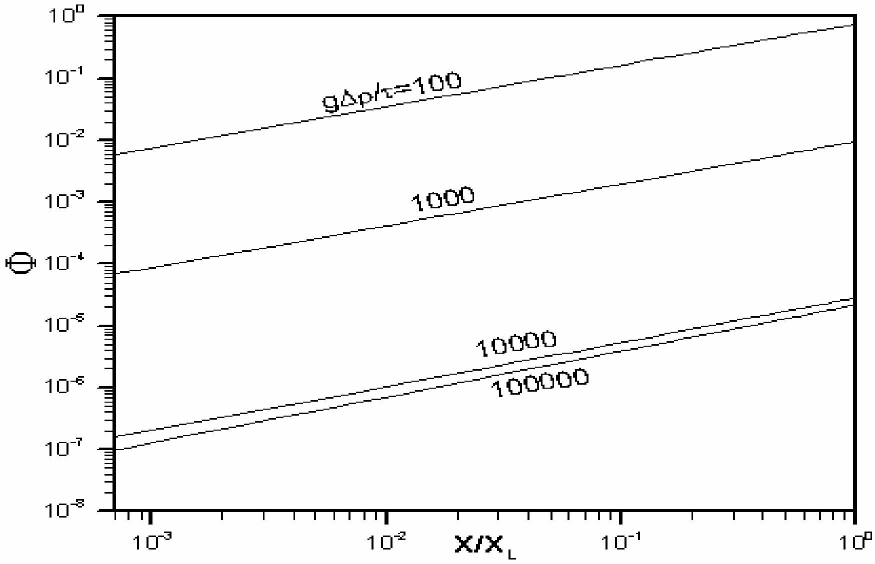

Fig.5 The effect of interfacial shear stress on entropy generation ratio

Conclusions

An analytical study was performed on the entropy generation minimization of film condensation on an isothermal flat plate. The problem can be categorized as:

- condensation with no interfacial shear ($B \to 0$)
- condensation with high interfacial shear ($B \to \infty$)

In both categories, it is proved analytically that an optimum condition exists between the thermal and frictional sources of entropy generation. According to these limiting cases, it is logical to conclude that the problem of film condensation in general form has an optimum solution which is a function of Ra/Ja and can be applied in various practical applications to maintain the least entropy generation. The results show that entropy generation minimization can serve as a useful tool in optimization of the two-phase thermal systems.

Nomenclature

C_p	specific heat at constant pressure, J/Kg.K
g	gravity acceleration, m/s^2
h_{fg}	Enthalpy, J/Kg.K
Ja	Jacob number
k	thermal conductivity, W/m.K
L	plate length, m
N_S	entropy generation number
Pr	Prandtl number
$\dot{P}_S''$	The volumetric entropy generation rate
q	heat transfer, J
Ra	Rayleigh
Re	Reynolds number
T	temperature, K
u	x-velocity component, m/s
v	y-velocity component, m/s
x	vertical coordinate
y	horizontal coordinate

Greek Letters

α	thermal diffusivity, m^2/s
δ	thickness of the condensate layer, m
ρ	density, Kg/m^3
μ	dynamic viscosity, Kg/m.s
υ	kinematic viscosity, m^2/s
τ	interfacial shear stress

Subscripts

L	plate length
opt	optimum
sat	saturated
T	thermal
v	vapor
V	Frictional
w	wall

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