

A More Accurate Prediction of Liquid Evaporation Flux

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ABSTRACT: *In this work, a more accurate prediction of liquid evaporation flux has been achieved. The statistical rate theory approach, which is recently introduced by Ward and Fang and exact estimation of vapor pressure in the layer adjacent to the liquid–vapor interface have been used for prediction of this flux. Firstly, the existence of an equilibrium layer adjacent to the liquid-vapor interface is considered and the vapor pressure in this layer and its thickness calculated. Subsequently, by using the Fick's second law, an appropriate vapor pressure expression for the pressure of equilibrium layer is derived and by this expression and the statistical rate theory approach, evaporation flux is predicted more accurately than the previous work. Finally, some novel steady state evaporations are simulated and the effects of both liquid and vapor temperature and the effect of the length of the evaporation chamber on the evaporation flux are investigated.*

KEY WORDS: *Evaporation, Condensation, Flux, Statistical rate theory, Water, Liquid interface, Vapor pressure.*

INTRODUCTION

Many expressions have so far been used to predict the evaporation (or condensation) flux. Hertz and Knudsen relations are the first being used in such attempts [1]. Some models based on the Boltzmann equation have been used to predict the existing conditions at the surface of an evaporating liquid [2-8]. These models have several adjustable parameters and are too complicated for practical applications. A new approach, based on statistical rate theory (SRT) has been introduced by Ward and Fang [9], which yields results that are in good agreement with the experimental data while at the same

time all of the thermodynamic variables which influence the evaporations rate are presented. The theory behind this approach is introduced briefly in section 2. The approach does not have any adjustable parameter and its accuracy is determined by the accuracy of the measurement or estimation of value of thermodynamics variables.

In section 3, the effect of errors in the measured vapor pressure, p^v , on the results obtained from the SRT equation is studied. Further, the existence of a vapor layer adjacent to the liquid surface with a pressure close to the

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equilibrium pressure is predicted in an open system and the thickness of this layer is calculated.

In section 4, the Fick's second law is used to derive a new accurate expression for p^v . The use of such an expression in the SRT equation gives a more accurate evaporative flux.

In section 5, the SRT equation along with the accurate vapor pressure expression is used to simulate new steady states both for evaporation and condensation processes. With the aid of these simulations, the steady state pressure at the orifice of the vacuum pump is calculated.

STATISTICAL RATE THEORY

The SRT expression for long evaporation time was derived with the approximation of the steady state evaporation, along with the assumption that chemical potential and temperature of both liquid and vapor phases remain constant during evaporation. With such approximations, the SRT expression for a flat surface is obtained as [9]:

$$j = \frac{p(T^l)}{\sqrt{2\pi mkT^l}} \left[\exp\left(\frac{\Delta s}{k}\right) - \exp\left(\frac{-\Delta s}{k}\right) \right] \quad (1)$$

$$\frac{\Delta s}{k} = 4 \left(1 - \frac{T^v}{T^l} \right) + \left(\frac{1}{T^v} - \frac{1}{T^l} \right) \sum_{i=1}^3 \left(\frac{\theta_i}{2} + \frac{\theta_i}{\exp(\theta_i/T^v) - 1} \right) +$$

$$\frac{v^l}{kT^l} (p^v - p(T^l)) + \ln \left[\left(\frac{T^v}{T^l} \right)^4 \frac{p(T^l)}{p^v} \right] + \ln \left(\frac{q_{\text{vib}}(T^v)}{q_{\text{vib}}(T^l)} \right)$$

Where j is the evaporative flux, $p(T^l)$ is the equilibrium vapor pressure at the liquid surface temperature T^l , m is the particle mass, Δs is the entropy change, k is the Boltzmann constant, T^v is the vapor temperature, v^l is the liquid volume per molecule, θ_i is the vibrational characteristic temperature of the i -th vibrational mode, p^v is the vapor pressure, and $q_{\text{vib}}(T)$ is the vibrational partition function.

Note that Eq.(1) has two advantages over its corresponding classical equation, which is based on the Boltzmann equation. First, it is expressed in terms of some measurable quantities which may be evaluated by using the experimental data [10]. Second, this equation may be used to predict all thermodynamic conditions under which the evaporation can occur. On the basis of the results of the works based on the

Boltzmann equation, evaporation occurs only when the temperature of the vapor phase is lower than that of the liquid phase. On the basis of Eq. (1), however, we may conclude that in order to have a net evaporation flux, the Δs value has to be positive. Note that when T^v is greater than T^l , the first and second terms on the right hand side of Eq. (1) become negative while the fourth and fifth terms become positive. The ratio of $p(T^l)$ to p^v in the fourth term and $p^v - p(T^l)$ in the third term have opposite effects on the sign of Δs in Eq. (1). Unlike the classical prediction [2-8], for the cases that $p^v > p(T^l)$ or $T^v > T^l$ evaporation still may occur. This conclusion is in accordance with the experimental results [10].

In spite of the advantages mentioned above, the SRT equation has a serious disadvantage in practical applications. The thermodynamic parameters in this equation, such as T^l , T^v and p^v , are defined only either for the interface or very close to it. Measurement of these parameters, especially p^v , in a very thin layer is difficult and may lead to serious errors in the prediction of the evaporation flux. From the practical point of view, these errors make the SRT equation almost useless.

EFFECT OF ERRORS INVOLVED IN THE MEASURED VAPOR PRESSURE ON PREDICTION OF EVAPORATION FLUX

Ward and Fang measured T^l , T^v and j for water using precise experimental methods [10]. By using very fine and sensitive thermocouples, the liquid temperature in the distance range of 0.1 to 0.3 mm from the liquid surface was measured. They have also measured vapor temperature in a layer span from interface to 1-5 times the mean free path. In measuring the pressure, a U-shaped mercury tube positioned near the liquid surface was used. Another gauge was placed near the vacuum pump about 0.4 m away from the liquid surface. Under their experimental conditions (e.g. $t = 25.5$ °C) they measured surface tension and specific electrical resistance of water to be 71.6 ± 1.2 N m⁻¹ and 15.0 MΩ cm, respectively. In their experiments, the evaporating liquid has a curved surface and Eq. (1) would become as [9]:

$$\frac{\Delta s}{k} = 4 \left(1 - \frac{T^v}{T^l} \right) + \left(\frac{1}{T^v} - \frac{1}{T^l} \right) \sum_{i=1}^3 \left(\frac{\theta_i}{2} + \frac{\theta_i}{\exp(\theta_i/T^v) - 1} \right) + \quad (2)$$

$$\frac{v^1}{kT} \left(p^v + \frac{2\gamma^{lv}}{R_c} - p(T^1) \right) + \ln \left[\left(\frac{T^v}{T^1} \right)^4 \frac{p(T^1)}{p^v} \right] + \ln \left(\frac{q_{vib}(T^v)}{q_{vib}(T^1)} \right)$$

Where R_c is the radius of the curvature and γ^{lv} is the surface tension. As reference and for comparative purposes, the experimental results obtained by Ward and Fang are reported in table 1. It can be seen from this table that the measured evaporation flux, j_{meas} , is quite different with that obtained from the SRT equation, j_{SRT} .

Even though the measured values of j , R_c , T^v and T^1 , in the experiments carried out by Ward and Fang are accurate, the error in the measured values of p^v is about ± 13.3 Pa [10]. As mentioned in Ref. (10), Eq. (2) may be differentiated to give

$$\frac{\Delta j}{j} = - \left(\frac{\Delta p^v}{p^v} \right) \coth \left(\frac{\Delta s}{k} \right) - \frac{2v^1 \gamma^{lv}}{kT^1} \frac{\Delta R_c}{R_c^2} \coth \left(\frac{\Delta s}{k} \right) + \left[\left(\frac{h^v}{kT^1} - \frac{1}{2} \right) + \left(\frac{h^v}{kT^1} - 4 \right) \coth \left(\frac{\Delta s}{k} \right) \right] \frac{\Delta T^1}{T^1} + \left[4 \left(1 - \frac{T^v}{T^1} \right) + \frac{1}{T^{v2}} \sum_{i=1}^3 \frac{\theta_i \exp(\theta_i / T^v)}{[\exp(\theta_i / T^v) - 1]^2} \right] \times \frac{\Delta T^v}{T^v} \coth \left(\frac{\Delta s}{k} \right)$$

This equation can be used to predict the effect of errors in the measured values of p^v , R_c , T^v and T^1 on the relative error of the calculated values of j . Ward and Fang used the data of their last experiment to reduce Eq. (3) to

$$\frac{\Delta j}{j} = - \left(\frac{8.0}{Pa} \right) \Delta p^v - \left(\frac{31.8}{K} \right) \Delta T^1 - \left(\frac{0.12}{K} \right) \Delta T^v - \left(\frac{7 \times 10^{-5}}{m} \right) \Delta R_c \quad (4)$$

On the basis of Eq. (4), the error of ± 13.3 Pa in the measured vapor pressure causes an error in j , which is more than 100 times of the evaporation flux itself. While,

Table 1: Comparison of measured values of evaporation flux [10] with calculated values of the evaporation flux using SRT.

Exp. No.	Measured evaporation flux j_{meas} ($g\ m^{-2}\ s^{-1}$)	Calculated evaporation flux by the SRT j_{SRT} ($g\ m^{-2}\ s^{-1}$)
1	0.2544	9.168
2	0.2799	13.517
3	0.3049	11.221
4	0.3480	7.914
5	0.3703	16.905
6	0.3971	23.162
7	0.4081	15.920
8	0.4097	3.471
9	0.4166	6.377
10	0.4166	12.372
11	0.4347	12.618
12	0.4860	15.783
13	0.4938	14.238
14	0.5086	13.880
15	0.5386	13.789

the error in T^1 or T^v , ± 0.1 K, has a negligible contribution to Δj . According to the data reported in Ref. [10], the measured pressure, p^v , is different from the effective pressure controlling evaporation, p^{eff} . Such effective pressure will be studied in the following section.

Existence of an equilibrium vapor layer

To find the effective pressure, we substitute the experimental values of j , T^v , T^1 and R_c measured by Ward and Fang into the SRT equation. The uncertainties of these quantities have negligible effect on the evaporation flux. The value of $p(T^1)$ is calculated based on the Clausius-Clapeyron equation and using $T^* = 273.16$ K and $p^* = 611$ Pa as reference values, and assuming that ΔH_{vap} is constant for the temperature range of Ward and Fang experiments and is equal to 45.05 $kJ\ mol^{-1}$. By comparing p^v from Ref. [10], p^{eff} and $p(T^1)$, we can conclude

that there exists a vapor layer adjacent to the liquid surface with a pressure close to the equilibrium vapor pressure.

In all previous models, the existence of an equilibrium vapor layer adjacent to the liquid surface is assumed as a basic approximation [2-8]. The existence of such a layer has also been proved, experimentally [11]. Comparison of j_{SRT} with j_{meas} values given in Table 1, suggests that the evaporation rate is decreased significantly due to the existence of such a layer.

Calculating thickness of the equilibrium vapor layer

The Fick's first law for ideal gas, Eq. (5), is used to calculate the thickness of this layer

$$j = \frac{-MD_{AB}}{RT} \frac{\partial p}{\partial x} \quad (5)$$

where D_{AB} is the diffusion coefficient of gas A molecules in gas B, M is the molar mass, and x is the distance from the liquid surface.

Since the SRT equation is derived on the basis of steady state approximation, we may expect that the evaporation flux to be equal to the diffusion flux of the vapor to the upper open space. If the width of a layer, Δx , is assumed to be very small e.g. $\Delta x \rightarrow 0$, Eq. (5) can be rewritten as

$$j = \frac{-MD_{AB}}{RT} \frac{\Delta p}{\Delta x} \quad (6)$$

In this equation T should be replaced with T^v as this equation applies for the equilibrium layer in the gas phase only. For this equilibrium layer, we have $\Delta x = x - 0 = x$ and $\Delta p = p^{eff} - p(T^1)$. By substituting these values for Δx and Δp into Eq. (6), we obtain the following equation for small x

$$x = \frac{MD_{AB} \left[p(T^1) - p^{eff} \right]}{jRT^v}$$

For a single-phase system, the following equation can be used to calculate the diffusion coefficient in the gas phase [12],

$$D = \frac{2}{3\bar{p}\sigma} \left(\frac{(kT^v)^3}{\pi m} \right)^{1/2} \quad (7)$$

where \bar{p} is the average pressure of the layer and σ is the

molecular cross section. Also, Eq. (8) is used to calculate the mean free path [13].

$$\lambda = \frac{V}{\sqrt{2}\pi d^2 N} = \frac{RT^v}{\sqrt{2}\pi d^2 p^v N_A} \quad (8)$$

where d is the diameter of a molecule and N_A is the Avogadro's number. The x/λ ratio has been calculated. The results show that x/λ ranges from 1.6 to 1.8.

In order to obtain accurate predictions of evaporation characteristics from the SRT equation, accurate values for T^v and p^v of the vapor layer should be known. In the experimental work, temperature of the vapor layer has been measured at different distances from the liquid interface ranging from 1 to 5 times of the mean free path, while pressure was measured at a distance quite far away from the interface [10]. Therefore, the measured pressure is not appropriate to be used in the SRT equation, and using such a pressure causes a significant error in the calculated value of j . The appropriate pressure will be discussed in the following section.

MORE ACCURATE PREDICTION OF THE LIQUID EVAPORATION FLUX

Since the measurement of pressure of the vapor layer close to the interface is very difficult, we may use the Fick's second law to derive an expression for the vapor pressure

$$\frac{\partial p(x,t)}{\partial t} = D \frac{\partial^2 p(x,t)}{\partial x^2} \quad (9)$$

This equation is valid when the system is not in steady state. To solve Eq. (9), we must first specify the boundary conditions for the system as:

$$p(0,t) = p(T^1) \quad (10-a)$$

$$p(\infty,t) = p^{vac} \quad (10-b)$$

$$p(x,0) = p^{vac} \quad (10-c)$$

The last one denoting the initial conditions. The boundary condition (10-a) indicates the pressure of the equilibrium layer at $x = 0$ while the boundary condition (10-b) indicates the existence of a vacuum pump in the system located at $x = \infty$, by which the steady state is established. The initial condition (10-c) shows that the pressure is uniform and equal to p^{vac} over the entire system before evaporation. This condition also requires

that the vacuum pump be turned on long before evaporation starts.

It can be shown that, the pressure at the orifice of the vacuum pump, p^{vac} , is related to the evaporation flux in the steady state by the following equation

$$p^{\text{vac}} = (2\pi mkT^{\text{vac}})^{1/2} j \frac{N_A}{M} \quad (11)$$

where T^{vac} is the temperature of the gas at the orifice of the vacuum pump. This equation holds only at the steady state, in fact, when the boundary condition (10-b) is satisfied.

The Laplace transform of the time domain of Eq. (9) may be used to solve this equation. $U(x,s)$ is the Laplace transformation of $p(x,t)$,

$$U(x,s) = L[p(x,t)] \quad (12)$$

and the Laplace transform of the time differential of $p(x,t)$ is

$$L\left[\frac{\partial p(x,t)}{\partial t}\right] = sL[p(x,t)] - p(x,t=0) \quad (13)$$

by considering the initial condition (10-c) and using Eq. (12), Eq. (13) will be reduced to

$$L\left[\frac{\partial p(x,t)}{\partial t}\right] = sU(x,s) - p^{\text{vac}} \quad (14)$$

By substituting Eqs. (12) and (14) into the Laplace transform of Eq. (9), we will find that

$$sU(x,s) = DU_{xx}(x,s) + p^{\text{vac}} \quad (15)$$

The Laplace transform of the boundary conditions (10-a) and (10-b) are:

$$U(0,s) = f_s = \frac{p(T^1)}{s} \quad \text{and} \quad U(\infty,s) = \frac{p^{\text{vac}}}{s}$$

$$\text{where } f_s = L[p(T^1)] \quad (16)$$

The solution of Eqs. (15) and (16) can be derived as below:

$$U(x,s) = \left(\frac{p(T^1) - p^{\text{vac}}}{s}\right) \exp\left(-\sqrt{\frac{s}{D}}x\right) + \frac{p^{\text{vac}}}{s} \quad (17)$$

By using the inverse Laplace transform of Eq. (17) we have:

$$p(x,t) = (p(T^1) - p^{\text{vac}}) \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right) + p^{\text{vac}} \quad (18)$$

Extrapolation of $p(x,t)$ at very small x gives p^{eff} . To apply Eq. (18) for the steady state, the time to reach the steady state, t_{ss} , is needed. The distance between the interface and the vacuum pump orifice, the diffusion coefficient and the temperature of the interface also must be known.

The pressure at the orifice of the vacuum pump can be obtained by using Eq. (11). For the experiments given in Ref. [10], the distance between the interface and the vacuum pump is reported to be about 0.4 m [10]. Under such conditions, system reaches the steady state in a fraction of a second after evaporation begins. In table 2, the temperature of the orifice of the vacuum pump, T^{vac} , taken from Ref. 10, and the calculated values of evaporation flux, the pressure at the orifice of the vacuum pump, p^{vac} , and the time needed for establishment of the steady state, t_{ss} , are reported. The method of calculation is as follows; the values of $p(x,t)$ at $x = 0.4$ m is obtained at different periods of time, Fig. 1. At the moment that $p(0.4,t)$ exceeds the value of p^{vac} , the evaporated molecules have reached the orifice of the vacuum pump, and have been distributed over the entire system. In other words, we have a static state at the orifice of the vacuum pump as long as the pressure is kept constant at p^{vac} (implying that the evaporated molecules have not yet reached the orifice) and the system is not at the steady state. When the wave of the evaporated molecules reaches the orifice, it is expected that a pressure change would occur. This is in contradiction with the boundary condition (10-b). Because of the suction of the vacuum pump, this expected change will never occur. However, it can be assumed that at the time corresponding to this expected pressure change, the system will reach its steady state.

Finally, after evaluating all variables of Eq. (18), the effective pressure at a distance 2λ , which is about the thickness of the equilibrium layer, from the surface of the liquid is calculated. In the sixth column of Table 2, the evaporation flux is calculated accurately, j_{cal} , by using the p^{eff} instead of p^{v} in the SRT equation. The corresponding j_{SRT} values are also reported there for comparison.

RESULTS AND DISCUSSION

Having values of the temperature of both the liquid surface and the vapor, it is possible to simulate the steady state under new conditions. This may be done by using

Table 2: calculated values of p^{vac} , t_{ss} , p^{eff} and j_{cal} using SRT equation based on the p^{eff} values.

Exp. No.	Measured evaporation flux	Temperature at the orifice of the vacuum pump	Pressure at the orifice of the vacuum pump	steady state establishment time	Effective vapor pressure	Calculated evaporation flux of this work	Calculated evaporation flux by the SRT
	j_{meas} ($g\ m^{-2}\ s^{-1}$)	T^{vac} (K)	p^{vac} (Pa)	t_{ss} (s)	p^{eff} (Pa)	j_{cal} ($g\ m^{-2}\ s^{-1}$)	j_{SRT} ($g\ m^{-2}\ s^{-1}$)
1	0.2544	296.76	0.2360	0.0855	497.063	0.6300	9.168
2	0.2799	300.06	0.2611	0.1005	601.711	0.6103	13.517
3	0.3049	297.26	0.2831	0.0744	431.266	0.5780	11.221
4	0.3480	298.26	0.3236	0.0590	345.866	0.4271	7.914
5	0.3703	297.26	0.3438	0.0552	317.683	0.5244	16.905
6	0.3971	301.66	0.3714	0.0590	343.206	0.2194	23.162
7	0.4081	298.66	0.3798	0.0476	376.007	0.3500	15.920
8	0.4097	298.56	0.3812	0.0463	265.349	0.3644	3.471
9	0.4166	299.26	0.3880	0.0428	247.869	0.4337	6.377
10	0.4166	298.46	0.3875	0.0713	418.456	0.5930	12.372
11	0.4374	297.06	0.4034	0.0489	282.592	0.3646	12.618
12	0.4860	300.56	0.4537	0.0476	276.000	0.3053	15.783
13	0.4938	301.36	0.4616	0.0418	239.324	0.1832	14.238
14	0.5086	300.56	0.4748	0.0381	219.134	0.2266	13.880
15	0.5386	301.26	0.5034	0.0350	200.493	0.1845	13.789

Eq. (18) and the SRT equation in a loop described as follows.

First, by knowing T^v , T^l , and an estimated initial guess value for p^v , $p^{v(0)}$, the initial value of j , $j^{(1)}$, is calculated using the SRT equation. This value of j is then substituted into Eq. (11), and its corresponding p^{vac} value, $p^{vac(1)}$, is obtained. Using Eq. (18), the value of p^{eff} calculated. This set of calculations may be repeated, but with $p^{eff(1)}$ instead of $p^{v(0)}$ from which $j^{(2)}$ and $p^{eff(2)}$ are computed. This iterative approach can be repeated until the $|j^{(n)} - j^{(n-1)}|$ difference reaches a convergence criteria. Two examples for such a loop are reported in table 3 for the first and last experiments of Ref. [10]. As can be seen the real values of p^v are quite different from the estimated initial values of p^v . However, the calculated j converges effectively after a few iterations. Now, the simulation of new steady state is possible without having any experimental data; each parameter may be changed and its effect on the evaporative flux can be investigated.

Effect of the length of the evaporation chamber on the evaporation flux

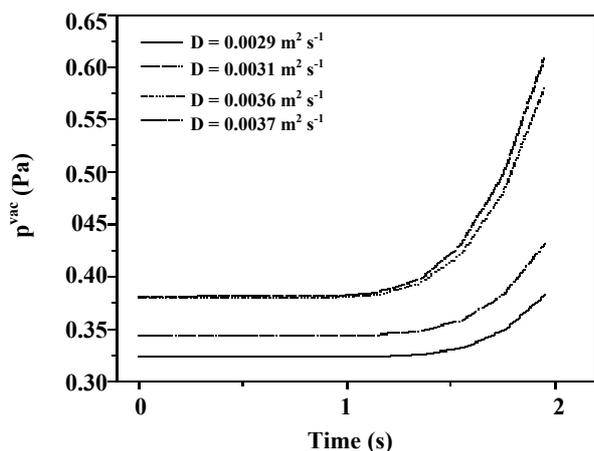
To find the effect of the change in the distance between the liquid surface and the orifice of the vacuum pump, x^{vac} , on the evaporative flux, we have considered the third experiment of Ref. [10]. By considering a new value for the length of the chamber, the time needed for the system to reach the steady state, t_{ss} , is calculated and then p^{eff} and evaporation flux are calculated consequently. In all calculations, we have assumed that the temperature is uniform throughout the evaporation chamber. The effect of such changes is shown in Fig. 2. As shown in this figure, by increasing the length of the chamber, the pressure gradient decreases and p^{eff} becomes closer to $p(T^l)$ and therefore, the evaporation flux decreases.

Effect of the liquid surface temperature on the evaporation flux

At constant T^v , the effect of T^l on the evaporation flux can be obtained. For a new value of T^l , the values of $j^{(1)}$ and $p^{eff(1)}$ may be calculated. By repeating this

Table 3: Convergence of the iterative solution of Eqs. (11) and (18) for p^{eff} and j_{cal} given in Pa and $g\ m^{-2}\ s^{-1}$, respectively.

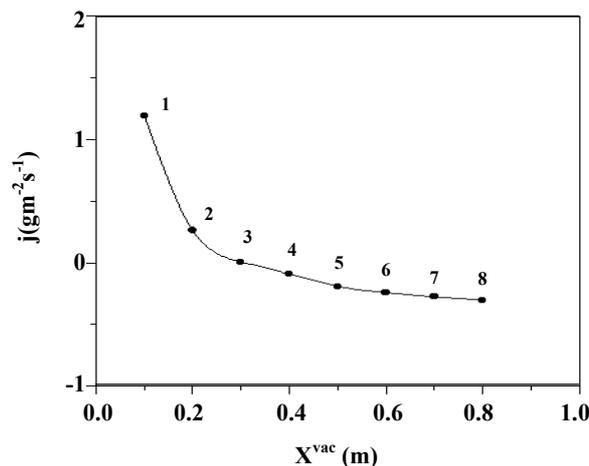
1	$p^v(0) = 400$ $T^v = 247.06$ $T^l = 270.36$	$j^{(1)}$	$p^{eff(1)}$	$j^{(2)}$	$p^{eff(2)}$	$j^{(3)}$	$p^{eff(3)}$	$j^{(4)}$
		246.657	497.444	-0.231	497.370	-0.064	497.370	-0.064
15	$p^v(0) = 180$ $T^v = 266.66$ $T^l = 258.66$	$j^{(1)}$	$p^{eff(1)}$	$j^{(2)}$	$p^{eff(2)}$	$j^{(3)}$	$p^{eff(3)}$	$j^{(4)}$
		50.307	200.835	-0.606	200.798	-0.521	200.188	-0.521

**Fig. 1: Pressure at the orifice of the vacuum pump, p^{vac} , plotted versus time, t , for various values of D .**

calculation as many times as needed the steady state under new condition (new value of T^l) can be obtained. By using the parameters of this new steady state, the value of the evaporation flux can be calculated. The effect of the surface temperature on j is shown in Fig. 3. Existence of a maximum on the j - T^l curve in this figure is due to the opposite effects of T^l and $p(T^l)$ in the SRT equation. As shown in section 1, increasing of T^l causes the evaporation flux to be increased due to the first and second terms in the SRT equation, and to be decreased due to the fourth and fifth terms. The effect of $p(T^l)$ on the flux is more complex. Increasing of $p(T^l)$ causes the evaporation flux to be decreased due to the third term and to be increased due to the fourth term. However, the increasing of $p(T^l)$ increases the p^v , and hence its effect on the flux is opposite to that of $p(T^l)$.

Effect of temperature of the vapor layer close to the interface on the evaporation flux

The effect of temperature of the vapor layer close to the interface on the evaporation flux can be studied by

**Fig. 2: Effect of the length of the evaporation chamber on the evaporation flux. Numbers on the points correspond to $p^{eff} = 430.997, 431.405, 431.519, 431.594, 431.606, 431.628, 431.643, \text{ and } 431.654$ Pascal.**

changing T^v while the other variables such as T^l and R_c , are held constant. For such a study, the data of experiment 8 may be used.

A change in the T^v value causes a change in the j value, and hence changes the p^{vac} value, and therefore, a new steady state will be produced. In Fig. 4, evaporation flux is plotted versus T^v . Note that the effect of T^v on p^{eff} is negligible, in such a way that it changes from 265.65 to 265.33 Pa when T^v changes by 19 K. The existence of a maximum in Fig. 4 is mainly due to the two opposite effects of T^v in the SRT equation.

Effect of the temperature of the vacuum pump orifice on the evaporation flux

To our knowledge, no experiment or calculation on the influence of vacuum pump orifice temperature on the evaporation flux has been reported. By using the data of experiment 10, the effect of T^{vac} on the p^{vac} , t_{ss} , p^{eff} and

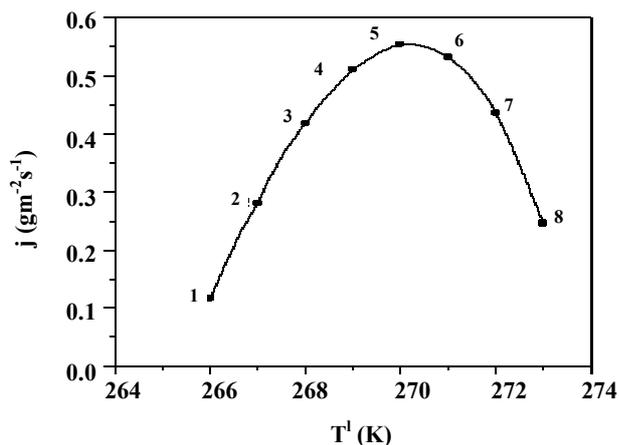


Fig. 3: The evaporation flux, j , plotted versus liquid surface temperature, T^l . Number on the points correspond to $p^{eff} = 358.04, 386.42, 416.82, 449.36, 484.16, 561.15, \text{ and } 603.63$ Pascal.

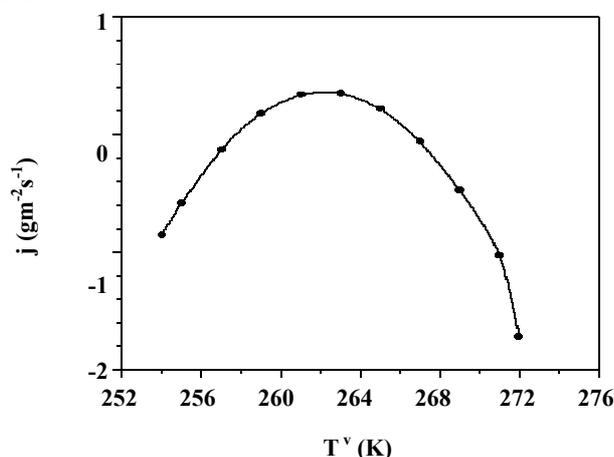


Fig. 4: The evaporation flux, j , plotted versus vapor temperature, T^v . The corresponding effective pressure changes from 265.65 Pa to 265.33 Pa.

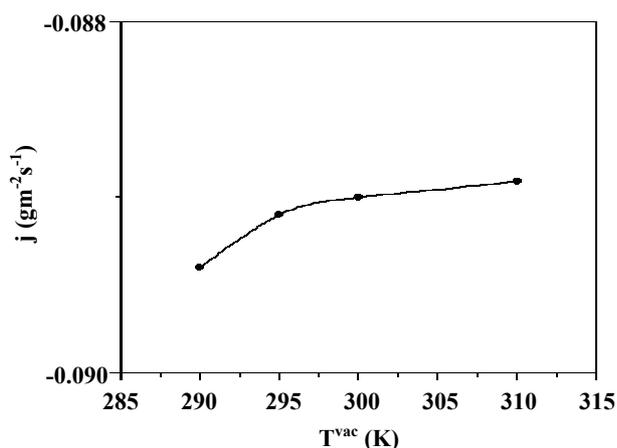


Fig. 5: The evaporation flux plotted versus temperature at the orifice of the vacuum pump, T^{vac} . Within the accuracy of the present calculations, no significant change is observed.

finally, on the evaporation flux may be investigated. As shown in Fig. 5, a change in the temperature of the vacuum pump orifice by 20 K changes evaporation flux by less than 0.1%.

CONCLUSIONS

Results of the present study show that by using the vapor pressure expression, Eq. (18), and the SRT equation, one can calculate either the evaporation or condensation flux for any practical application without carrying out any measurement on P^v near the interface. For such an application, the distance between the interface and the vacuum pump orifice must be known accurately. In the absence of a vacuum pump, the distance between the interface and the boundary of the space over which pressure gradient is practically zero must be accurately determined.

In this work, we have considered the net evaporation flux. However, the SRT equation and the vapor pressure expression, introduced in this work, can be applied for both condensation and evaporation fluxes.

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List of symbols

σA	Surface area
D_{AB}	Diffusion coefficient of gas A molecules in gas B
h	Molecular enthalpy
j	Evaporation or condensation flux
j_{meas}	Measured evaporation flux
j_{cal}	Calculated evaporation flux in this work
j_{SRT}	Calculated evaporation flux by the SRT equation
k	Boltzmann constant
k_{lv}	Transfer probability per unit area from the liquid phase to the vapor phase
K_e	Equilibrium constant
L	Laplace operator
m	Particle mass
M	Molar mass
N_A	Avogadro's number

$p(T^l)$	Equilibrium vapor pressure at the temperature of the liquid surface
p^v	Vapor pressure
p^{eff}	Effective vapor pressure
\bar{p}	Average pressure of the equilibrium vapor layer
$q_{\text{vib}}(T)$	Vibrational partition function
R_c	Radius of the liquid surface curvature
s	Molecular entropy change
t_{ss}	Steady state establishment time
δt	Transition time
T	Absolute temperature
T^{vac}	Temperature of the vapor at the orifice of the vacuum pump
$U(x,s)$	Laplace transformation of $p(x,t)$
U^R	Internal energy of the heat reservoir
v^l	Liquid volume per molecule
x	Distance from the liquid surface
x^{vac}	Length of the evaporation chamber

Greek letters

γ^{lv}	Surface tension of liquid-vapor interface
θ_i	Vibrational characteristic temperature of the i-th vibrational mode
λ	Mean free path
λ_j	Molecular distribution of the j-th phase
μ	Molecular chemical potential
σ	Molecular cross section
$\tau[\lambda_j, \lambda_k]$	Molecular transition probability

Superscripts

l	Liquid phase
v	Vapor phase

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