THE EFFECT OF VAPOR SUBCOOLING ON FILM CONDENSATION OF METALS

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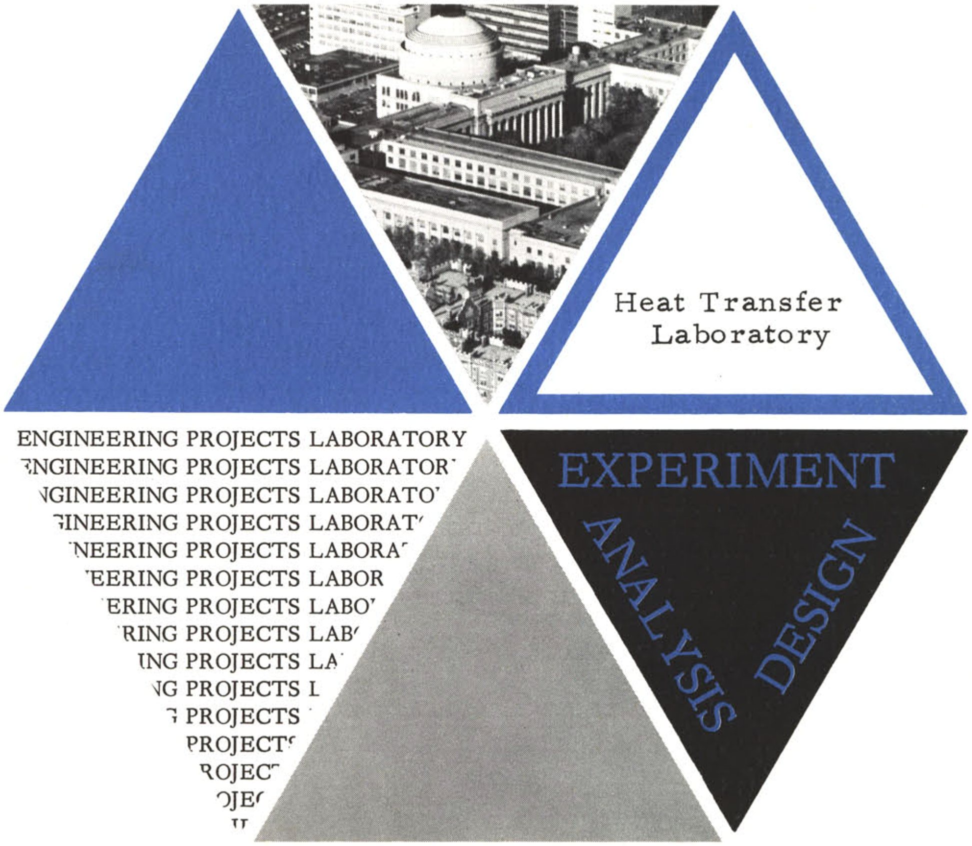

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ABSTRACT

This work presents an analysis of the interfacial "vapor-condensate" temperature distribution, which includes the effect of subcooling (supersaturation) in the vapor. Experimental data from previous investigators for different metals were analyzed.

It is shown that taking into account this subcooling effect permits the thermal interphase resistance to be described with assumption of σ = Constant = 1.0 where σ is the condensation (mass accommodation) coefficient.

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LIST OF FIGURES

NOMENCLATURE

A	area
a	thermal accommodation coefficient
c_p, c_v	heat capacities of the vapor
d	thickness of the discontinuity zone for temperature distribution (Knudsen zone)
G	relation between mass flow rate and temperature drop in the film, defined by Eq. (11)
g	gravitational acceleration
h_{fg}	latent heat of vaporization
h'_{fg}	latent heat, which includes change of enthalpy due to the subcooling of the liquid = $h_{fg} + 0.68\, c_\ell\, (T_s - T_w)$ c_ℓ - heat capacity of the liquid
k_v	thermal conductivity of vapor
k_ℓ	thermal conductivity of liquid
L	condenser plate length
M	molecular weight
p_v	bulk saturation pressure of the vapor
p_i	saturation pressure, which corresponds to temperature T_i of subcooled vapor
p_s	saturation pressure which corresponds to liquid surface temperature T_s
Pr	vapor Prandtl number
$(q/A)_{wall}$	measured heat flux
R	universal gas constant
T	temperature (identified by subscripts)
W/A	mass flux
X	coordinate, normal to the wall
δ	thickness of the condensate film
η	kinematic viscosity
λ	mean free path of the vapor molecules
μ	dynamic viscosity
ρ	density
σ	condensation coefficient
ξ	temperature jump coefficient

NOMENCLATURE (Continued)

Subscripts

c	condensation
i	interface
s	condensate surface
v	vapor
w	wall
l	liquid

INTRODUCTION

In the case of liquid metals film condensation the experimental heat fluxes for given vapor and wall temperatures were found to be much smaller (five to thirty times) (see for example, (1), (2)) in comparison with prediction by film theory (3). The most probable cause of the lower heat transfer rate is the presence of a thermal resistance of the liquid-vapor interface. This resistance was analyzed by means of the kinetic theory and the application of modified Hertz-Knudsen mass transfer equation was shown (4), (5):

$$\frac{W}{A} = \frac{2\sigma}{2-\sigma} \left(\frac{M}{2\,RT_i} \right)^{1/2} (p_v - p_s) \qquad (1)$$

The interphase mass transfer was also studied in detail in other works. It is worth noticing that neglecting the temperature gradient in the vapor is a shortcoming of present theory, as mentioned in (6), (7), and (8).

So, the analysis of liquid metals condensation data was based on using the Eq. (1) for the interphase resistance and Eq. (11) for the liquid film resistance. In this case condensation coefficient σ can be determined from experimental data because T_v, T_w and (q/A) are measured.

All the experimental results which have been received for potassium, sodium and mercury show the condensation coefficient changes with experimental conditions and decreases with increasing vapor pressure as shown in Fig. 1.

Actually no physical consideration is able to support this behavior of the condensation coefficient. Moreover, most of the theoretical predictions (14) and experiments with pure metal surfaces (1) showed σ to be close to unity.

PROPOSED MODEL

Kinetic theory of condensation describes the process purely in terms of mass transfer and consists of the assumption that bulk vapor conditions prevail up to the liquid surface, i.e., it neglects the possibility that interactions between evaporation (and reflecting) molecules and condensing molecules might alter the energy (temperature) of vapor molecules near the interface. In terms of the macroscopic mass and energy transport equations it indicates that the phenomenon is associated with subcooling of the vapor boundary layer adjacent to the liquid.

Bulk nucleation theory (15) which requires a substantial degree of supersaturation to maintain net nucleation, permits subcooling.

It has been suggested (6), (7) that the vapor subcooling effect must be included in a more precise theory. This idea was used for describing gradients in vapor properties in terms of the macroscopic transport equations for condensing superheated steam (16) and for analysis the condensation of steam at low pressures (7). However, the subcooling idea was not applied quantitatively to the analysis of liquid metal condensation data.

Let us consider a saturated vapor at uniform bulk temperature T_v in contact with the liquid film whose surface temperature T_s is <u>lower</u> than T_v. Therefore, heat transfer occurs from the vapor to the liquid and a non-zero temperature gradient exists in the vapor near the interface (Fig. 2.) The temperature profile in the vapor can be found from the solution of the differential equation for conduction in the flow to the condensate surface (neglecting the convection effect):

$$\frac{W}{A} C_p \frac{dT}{dx} = K_v \frac{d^2T}{dx^2} \qquad (2)$$

$$x = x_i \qquad T = T_i$$

$$x = \infty \qquad T = T_v$$

The solution is:

$$\frac{T_v - T}{T_v - T_i} = \exp\left(- \frac{\Delta x \left(\frac{W}{A}\right) C_p}{K_v} \right) \qquad (3)$$

In most cases the size of zone $\Delta x = x - d$ (Fig. 2), in which the vapor temperature changes significantly (i.e., when $(T_v - T)/(T_v - T_i) = 0.90$) will not be more than a few hundredths of an inch, which makes this subcooling effect very difficult to observe experimentally.

If the temperature gradient does exist rather than sharp discontinuity, $T_i - T_s < T_v - T_s$. The apparent condensation coefficient (see Fig. 1) defines by latter difference $(T_v - T_s)$. The true condensation coefficient would be greater, because it was calculated using the true difference $(T_i - T_s)$ or $(p_i - p_s)$.

ANALYSIS

Experience with heat transfer between rarefied gases and solid surfaces gives us from kinetic theory (17), (18) a relation between the temperature jump $T_i - T_s$ and the temperature gradient $(dT/dx)_i$ which we propose to apply here to the condensation process at the liquid-vapor interface. This relation is:

$$(T_i - T_s) = (\xi + d) \left| \frac{dT}{dx} \right| \tag{4}$$

where the temperature jump coefficient is given by:

$$\xi \cong \frac{2}{Pr} \quad \frac{2 - a}{a} \quad \frac{\frac{c_p}{c_v}}{\frac{c_p}{c_v} + 1} \lambda \tag{5}$$

Here T_i is the average temperature of molecules striking the surface and region of dimension d (Fig. 2) is known as the Knudsen zone and is the region where interaction between the molecules coming from the surface at T_s and the molecules going toward the surface prevail. The size of this zone is of the order of a few mean free paths. This distance is sometimes interpreted as the average distance from which the molecules striking a surface have their last collision. For the hard sphere model of a gas at uniform temperature in the absence of a solid surface d is calculated to be $2\lambda/3$. When a solid surface is present the magnitude may be in the range of λ to 5λ (18), and (19). It is probable that d at liquid-vapor interfaces is also of this order of magnitude.

Anticipating a conclusion that the mass accommodation coefficient σ is unity, we conclude that the thermal accommodation coefficient a in Eq. (5) is unity because with $\sigma = 1$ all of the molecules going toward the surfaces condense and the molecules leaving the surface are at T_s (15), (17), and (18). Then Eq. (5) becomes:

$$\xi \equiv \frac{2\lambda}{Pr} \frac{\frac{c_p}{c_v}}{\frac{c_p}{c_v} + 1} \tag{6}$$

This temperature jump coefficient may be seen from Eq. (4) to be interpreted graphically by the distance ξ shown in Fig. 2.

Because of the existence of the temperature jump $T_i - T_s$ in this condensation problem the process in the vapor can be tested in terms of the rarefied gas temperature jump (or slip) theory. The effect of the mass transfer on the coefficient ξ was considered by Mills (20) who showed that Eqs. (4) and (5) are valid provided the ratio of vapor bulk velocity toward the surface is small compared with the mean thermal velocity of the molecules, which is certainly true in any practical case of a condensing vapor.

An energy balance for the control volume between the plane at i and the vapor (Fig. 2) is:

$$\frac{W}{A} c p_v (T_v - T_i) = k_v \left(\frac{dT}{dx}\right)_i , \tag{7}$$

combining Eqs. (7) and (4) yields:

$$\frac{T_v - T_i}{T_i - T_s} = \frac{k_v}{\frac{W}{A} \; C_v (\xi + d)} \tag{8}$$

An over-all energy balance for a control volume between the wall and the vapor is:

$$\frac{q}{W}_{\text{wall}} = \frac{W}{A} \; h'_{fg} \tag{9}$$

where:

$$h'_{fg} = C_v (T_v - T_s) + h_{fg} + \frac{3}{8} \; C_\ell (T_s - T_w) \tag{10}$$

For determining the temperature drop across the liquid layer we use the ordinary Nusselt type analysis. This may be expressed as (21)

$$\frac{W}{A} = G (T_s - T_w) \tag{11}$$

where for a vertical plate:

$$G \equiv 0.943 \left[\frac{g\rho_\ell (\rho_\ell - \rho_v) k_\ell^{\,3}}{L \mu (T_s - T_w) h'^{\,3}_{fg}} \right]^{1/4} \tag{12}$$

and for a horizontal tube:

$$G \equiv 0.728 \left[\frac{g\rho_\ell (\rho_\ell - \rho_v) k_\ell^{\,3}}{D \mu (T_s - T_w) h'^{\,3}_{fg}} \right]^{1/4} \tag{13}$$

and

$$h'_{fg} \equiv h_{fg} + 0.68 \cdot c_{\ell} \cdot (T_s - T_w)$$

For the temperature jump $(T_i - T_s)$ Eq. (1) is revised as follows:

$$\frac{W}{A} = \frac{2\sigma}{2 - \sigma} \left(\frac{M}{2\pi R T_i}\right)^{1/2} (p_i - p_s) \qquad (14)$$

where p_i is the saturation pressure corresponding to T_i and p_s is the saturation pressure corresponding to T_s.

The use of p_s as the saturation pressure corresponding to T_s in Eq. (14) represents the flow rate of molecules leaving the liquid surface if the entire system were uniformly at the temperature T_s. The fact that the vapor is at T_i does not alter this rate of flow significantly. In other words, quasi-equilibrium is assumed. In a similar way we may use p_i as the saturation pressure corresponding to T_i to calculate the flow of vapor molecules toward the liquid surface if we postulate the existence of a small amount of homogeneous nucleation takes place in the subcooled vapor at T_i and that this condensate forms at the temperature T_i. Under these circumstances the energy balance Eq. (7) should really be written as follows:

$$k_v \left(\frac{dT}{dx}\right)_i = \frac{W}{A} \; c_{pv} (T_v - T_i) + \alpha \; \frac{W}{A} \; h_{fg} \qquad (15)$$

where α is the fraction of the mass flow to the surface which is condensed in the vapor by homogeneous nucleation. An evaluation of α from homogeneous nucleation theory (15) suggests that for the ranges of variables in the liquid metal data discussed here its magnitude is in the range of 10^{-3} to 10^{-5}. For the purpose of the present analysis, the term involving α in Eq. (15) will be neglected.

For a particular magnitude of d, Eqs. (8), (9), (11) and (14) permit the calculation of (q/A) at the wall for particular values of T_v and T_w, assuming $\sigma = 1$.

It will be shown in the next section that d taken equal to 10λ yields results in good agreement with experimental data.

RESULTS

The analysis described above was used to treat experimental data (9), (13), (1), (22), (12), (11), (2), (25), and (26), for mercury, potassium and sodium saturation vapor, condensing on vertical and horizontal surfaces in the saturation pressure range $p_s = 0.0001 \div 1.0$ atm.

The temperature jump coefficient, ξ , was calculated from Eq. (6).

The mean free path λ was calculated from the expression (see for example (23).)

$$\lambda = \frac{1}{\sqrt{2}\,\pi S(T) n} \text{ , cm.} \tag{16}$$

where

$$\pi S(T) = 266.93 \frac{\sqrt{M T_i}}{\mu 10^7}$$

(T - ^{o}k, μ - poises, n - numerical density of vapor, 1/cm^3).

The effect of dimerization was neglected for all the media. The properties of media were taken from (24) and were evaluated at temperature T_i for calculating λ .

The data provides measurements of $(q/A)_w$, T_v and T_s. From these and the equations suggested here the magnitude of σ may be calculated for any assumed value of d.

Figure 3 represents the condensation coefficient for recalculated data as a function of the pressure p_s for d = 10λ. The results for different vapors scattered about a horizontal straight line at $\sigma = 1.0$, except for the sodium data of Barry (13) and some of the mercury data of Misra and Bonilla (22).

CONCLUSIONS

1. Taking into account the vapor subcooling effect (neglecting the quantitative effect of homogeneous nucleation) near the liquid surface during film condensation of liquid metal vapors leads to the conclusion that the condensation coefficient σ is independent of pressure and is equal to unity when the Knudsen zone thickness d is taken as 10λ.
2. The suggested model employing Eqs. (8), (9), (11) and (14) with Eqs. (6) and (12) or Eq. (13) with the above magnitudes of $\sigma = 1$ and $d = 10\lambda$ may be used to predict heat flux associated with film condensation of saturated vapors.

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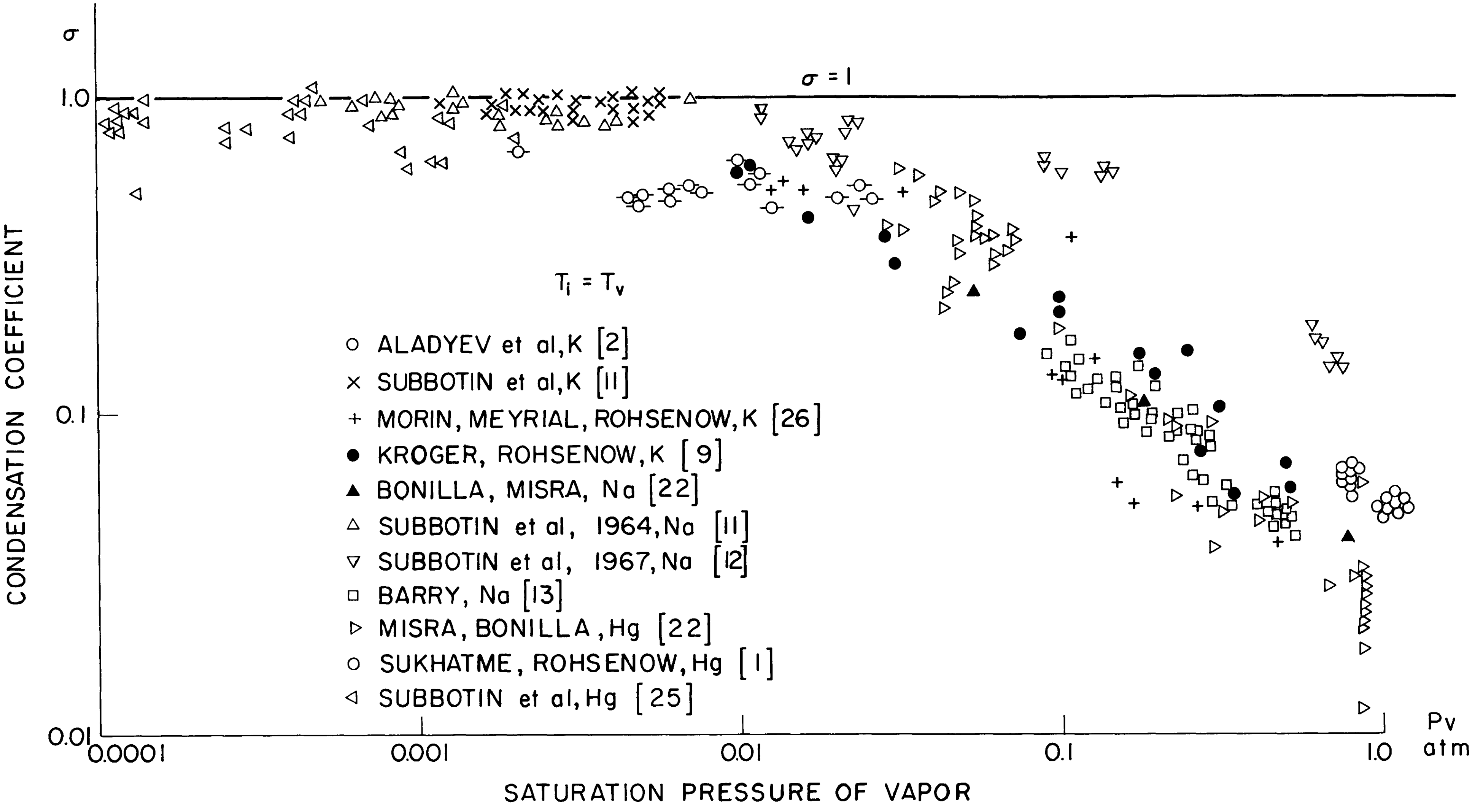
σ
σ = 1
1.0
0.1
0.01
CONDENSATION COEFFICIENT
$T_i = T_v$
○ ALADYEV et al, K [2]
× SUBBOTIN et al, K [11]
+ MORIN, MEYRIAL, ROHSENOW, K [26]
● KROGER, ROHSENOW, K [9]
▲ BONILLA, MISRA, Na [22]
△ SUBBOTIN et al, 1964, Na [11]
▽ SUBBOTIN et al, 1967, Na [12]
□ BARRY, Na [13]
▷ MISRA, BONILLA, Hg [22]
○ SUKHATME, ROHSENOW, Hg [1]
◁ SUBBOTIN et al, Hg [25]
0.0001
0.001
0.01
0.1
1.0
Pv atm
SATURATION PRESSURE OF VAPOR

FIG. 1

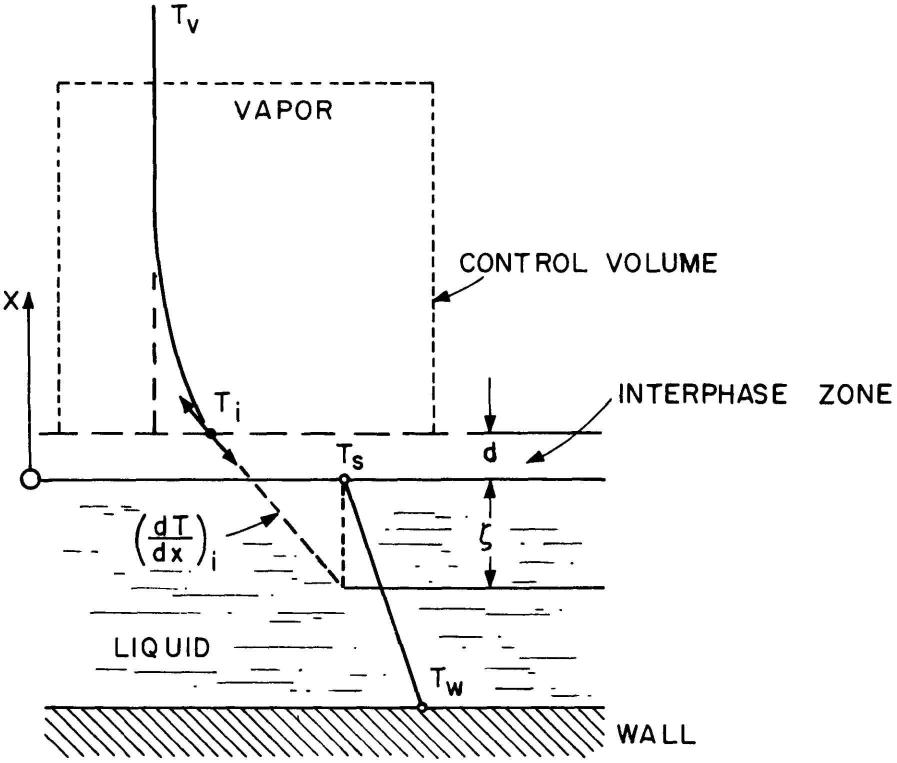
T_v
VAPOR
CONTROL VOLUME
X
T_i
INTERPHASE ZONE
d
T_s
$\left(\frac{dT}{dx}\right)_i$
ζ
LIQUID
T_w
WALL

FIG. 2

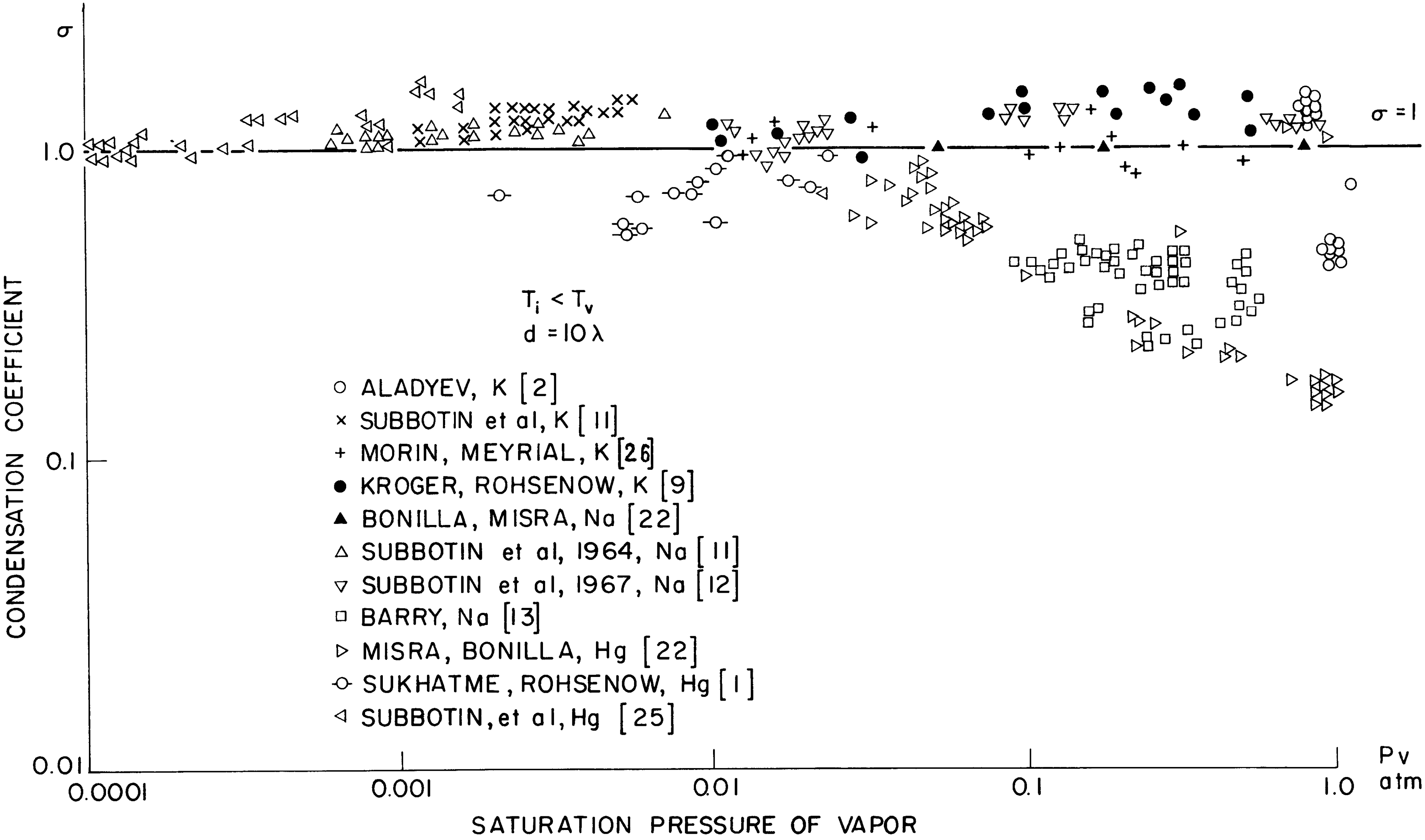
σ
CONDENSATION COEFFICIENT
1.0
0.1
0.01
σ = 1
$T_i < T_v$
d = 10 λ
○ ALADYEV, K [2]
× SUBBOTIN et al, K [11]
+ MORIN, MEYRIAL, K [26]
● KROGER, ROHSENOW, K [9]
▲ BONILLA, MISRA, Na [22]
△ SUBBOTIN et al, 1964, Na [11]
▽ SUBBOTIN et al, 1967, Na [12]
□ BARRY, Na [13]
▷ MISRA, BONILLA, Hg [22]
-○- SUKHATME, ROHSENOW, Hg [1]
◁ SUBBOTIN, et al, Hg [25]
0.0001
0.001
0.01
0.1
1.0
Pv atm
SATURATION PRESSURE OF VAPOR

FIG. 3