N71-23100

NASA TECHNICAL MEMORANDUM

NASA TM X-67808

NASA TM X-67808

MASS DIFFUSIVITY EFFECTS ON DROPLETS IN FILM BOILING

by Glen J. Schoessow
University of Florida
Gainesville, Florida

and

Kenneth J. Baumeister
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Twelfth National Heat Transfer Conference sponsored by the
American Society of Mechanical Engineers and the
American Institute of Chemical Engineers
Tulsa, Oklahoma, August 15-18, 1971

E-6268

MASS DIFFUSIVITY EFFECTS ON DROPLETS IN FILM BOILING

by Glen J. Schoessow* and Kenneth J. Baumeister**

ABSTRACT

This paper presents experimental film boiling data for water droplets vaporizing into air, argon, nitrogen, helium, and steam. A dimensionless grouping is presented which compares vapor removal by diffusion from the top of the drop to vapor removal by film boiling from the bottom of the drop. This dimensional grouping is in good agreement with the experimental data.

INTRODUCTION

Current research in droplet film boiling on hot surfaces is concerned with such problems as fuel vaporization in spark-ignition or diesel engines (ref. 1); spray cooling or quenching of heated surfaces (refs. 2 and 3); liquid droplet removal in mist sections of boilers (ref. 4); and in other diverse problems. References 1 to 12 contain a comprehensive current literature summary of the recent work in droplet film boiling as well as a discussion of the phenomenon.

Heat-transfer coefficient correlations for drops in film boiling have been based mostly on experimental data for drops exposed to air; however, in applications as above the drops usually vaporize in a saturated atmosphere of their own vapor. The present paper presents experimental film boiling data for water drops vaporizing into steam, air, argon, nitrogen and helium at atmospheric pressure.

Professor Bell (ref. 5) points that at the present time, we simply do not know enough about the temperature and velocity fields surrounding the drop to accurately assess diffusivity effects. "If the pure vapor from underneath the drop rises around the drop and enshrouds the upper surface

---

*University of Florida, Gainesville, Florida.

**NASA Lewis Research Center, Cleveland, Ohio.

(fig. 1(a)), then diffusive mass transfer can be neglected (though bulk evaporation could still take place). On the other hand, if the vapor from underneath the drop disperses radially outward away from the surface (fig. 1(b)), and the upper surface is in an air atmosphere, then molecular and possibly convective diffusion could occur. The fact that the droplet upper regions are usually a few degrees below saturation temperature tends to support the latter supposition. Wachters (ref. 6) interprets his observation that a droplet in air evaporates faster than a droplet in a saturated atmosphere, as indicating that diffusive mass transfer exists in the former case."

A flow visualization technique developed in reference 15 gives further credence to the two-region flow model. If a liquid nitrogen droplet is placed on a water surface instead of the conventional solid surface (see fig. 2), the liquid nitrogen drop will still enter a conventional film boiling state. Heat will be transferred to the liquid nitrogen droplet and the drop will begin to evaporate. However, as the nitrogen vapor moves along the water surface small amounts of water will diffuse into the nitrogen vapor and condense.

The flow field outlined by the condensed water vapor is quite similar to the two-region flow model in figure 1(b). However, the flow patterns seen by this visualization technique will not be exactly similar to that which occurs in conventional boiling. In conventional boiling, the vapor will generally be much hotter. In this case, bouyancy effects will tend to reduce the size of region 2. Nevertheless, this flow visualization technique is one more additional justification for the two-region model.

A movie of the developing vapor flow-field is available in a movie supplement to reference 15. Figure 3 shows a series of photographs taken from the movie. As seen in these photographs, the upper surface of the drop is not engulfed by the vapor; thereby leaving the upper surface of the drop exposed to allow diffusion and convection to occur.

Baumeister and Schoessow in reference 13 conceded the importance of diffusive effects at low plate temperature especially if the droplet is in the metastable Leidenfrost state (ref. 14). However, at high plate temperatures normally associated with droplet film boiling, they argued that diffusive evaporation from the upper surface will be negligible compared to boiling evaporation from the lower surface. Their justification was the agreement of the experimental data with their generalized theory which neglected diffusion. Their motivation for neglecting diffusion was the relative ease in obtaining a generalized closed form solution for the drop vaporization time.

If neglecting diffusion is a reasonable assumption for high temperature droplet film boiling in air, would the assumption also hold for droplet vaporization in nitrogen or another inert gas? At what temperature level in air would neglecting the diffusive effect lead to large errors? To answer these and other similar questions, a dimensionless grouping will be derived which compares vapor removal by diffusion from the top of the drop to vapor removal by film boiling from the bottom of the drop.

In particular, this paper will introduce a dimensionless group which can be used as a criteria for predicting when diffusion is important. Next, drop vaporization data are taken with various atmospheres and compared to the dimensionless group.

SYMBOLS

A	area
A_d	area of drop in which diffusion occurs
A_{fb}	area of drop in which film boiling heat transfer occurs
A_r	area of drop in which radiative heat transfer occurs
C_p	specific heat at constant pressure of vapor
D_{AB}	diffusion coefficient (see table II)
F	radiation view factor
Gr	defined by $\rho_V(\rho_L - \rho_V)gL^3/\mu^2$ evaluated at film temperature
g	coefficient of gravity
H	defined by $\lambda/C_p \Delta T$

H^*	defined by $\lambda^*/C_p\ \Delta T$
h_{fb}	film boiling heat transfer coefficient
h_r	radiative heat transfer coefficient
h_s^*	dimensionless heat transfer coefficient (see table I)
k	thermal conductivity of vapor
L	characteristic length defined as $[\sigma/g(\rho_L - \rho_V)]^{1/2}$
M	molecular weight
N_{DC}	dimensionless parameter defined by equation (11)
P	pressure
Pr	Prandtl number $C_p\mu/k$ evaluated at film temperature
P_s	saturation pressure
P_∞	vapor pressure far removed from drop
R	gas constant
r_o	effective droplet radius
r_o^*	dimensionless radius (see table I)
Sc	modified Schmidt number, $\mu/D_{AB}(MP_s/RT_s)$ with μ evaluated at film temperature
T	temperature
ΔT	temperature difference
T_p	plate temperature
T_s	saturation temperature
t	time
V	volume of liquid drop
V^*	dimensionless volume of liquid drop, V/L^3
W_d	rate of mass loss by diffusion per unit area

W_{fb}	rate of mass loss by film boiling per unit area
W_r	rate of mass loss by radiation per unit area
λ	latent heat of vaporization
λ^*	modified latent heat of vaporization, $\lambda\left(1 + \frac{7}{20}\frac{C_p\,\Delta T}{\lambda}\right)^{-3}$
μ	viscosity of vapor
ρ_L	liquid density
ρ_V	vapor density
σ	surface tension
$\bar{\sigma}$	Stefan-Boltzmann constant

DIMENSIONLESS PARAMETER

Gottfried, Lee, and Bell (ref. 8) subdivided a mass balance on a droplet in film boiling similar to the following:

$$W_dA_d + W_{fb}A_{fb} + W_rA_r = -\rho_L\frac{dV}{dt} \tag{1}$$

where W_d represents the rate of mass loss by diffusion per unit area, W_{fb} and W_r represents the rate of mass lost from the bottom and sides of the droplet by film boiling and radiation per unit area, and, of course, the right side of equation (1) represents the rate of change of the volume of the liquid drop. The mass loss by film boiling and diffusion are assumed to be mutually exclusive. The film boiling and radiation and component of mass transfer W_{fb} and W_r are given as

$$W_{fb} = \frac{h_{fb}\,\Delta T}{\lambda} \tag{2}$$

$$W_r = \frac{\bar{\sigma}F\left(T_p^4 - T_s^4\right)}{\lambda} = \frac{h_r\,\Delta T}{\lambda} \tag{3}$$

and W_d can be approximated as

$$W_d = \frac{D_{AB}M}{RT_s r_o} P_s \tag{4}$$

for a liquid at its saturation temperature and pressure. For this case, partial pressure of the liquid in the vapor environment is quite small and the log mean partial pressure of the inert gas is equal to the system pressure.

Substituting equations (2) to (4) into equation (1) gives

$$-\lambda\rho_L \frac{dV}{dt} = h_{fb}\,\Delta T A_{fb} + h_r\,\Delta T A_r + \lambda \frac{D_{AB}MP_s}{RT_s r_o} A_d \tag{5}$$

Since diffusion is expected to be important only at low ΔT, the radiative component of heat transfer is small compared to the film boiling component. Consequently, for the purpose of simplicity, radiation is now neglected. In this case, equation (5) becomes

$$-\lambda\rho_L \frac{dV}{dt} = h_{fb}\,\Delta T A_{fb} + \lambda \frac{D_{AB}MP_s}{RT_s r_o} A_d \tag{6}$$

Dividing both sides of equation (6) by the conductive heat transfer term gives

$$\frac{-\lambda\rho_L}{h_{fb}\,\Delta T A_{fb}} \frac{dV}{dt} = 1 + N_{DC} \tag{7}$$

where

$$N_{DC} = \frac{\lambda D_{AB}MP_s}{Rr_oT_sh_{fb}\,\Delta T} \frac{A_d}{A_{fb}} \tag{8}$$

Equation (7) could now be integrated to determine the total vaporization time of the drop subject to the restriction that radiation is small. Of course, the relationship between the heat transfer coefficient, heat transfer area, and drop volume must first be determined before the integration is performed.

In the application of equation (7) to small spherical drops, Gottfried and Bell (ref. 12) included the diffusion term which necessitated a numerical solution. On the other hand, Baumeister, Hamill, and Schoessow (ref. 9) related the drop size to volume for both spherical and large drops, neglected the diffusion term and obtained a simple closed-form solution to the problem.

A cursory examination of N_{DC} (eq. (8)) indicates that for large ΔT's, N_{DC} in equation (7) might be safely neglected. However, for small ΔT's, N_{DC} could become the dominant term in the mass balance (eq. (7)). To evaluate N_{DC} for comparison purposes, expressions for h_{fb} and r_o as a function of the droplet volume are required. The expressions for h_{fb} can be written as follows:

$$r_o = Lr_o^*(V^*) \tag{9}$$

$$h_{fb} = \frac{k}{L}(Gr\ Pr\ H^*)^{1/4} h_s^*(V) \tag{10}$$

where the expressions for the dimensionless parameters r_o^* and h_s^* are given in table I for various ranges of the dimensionless droplet volume V^*. The derivations of these expressions can be found in references 9 and 13. For large drop volumes, nonspherical drops, equations (8) and (9) represent approximations to the spherical case.

Substituting equations (9) and (10) into equation (8), taking the ratio of A_d/A_{fb} equal to 1, introducing the Schmidt number, and rearranging the terms gives

$$N_{DC} = \frac{H}{Sc}\left(\frac{Pr^3}{Gr\ H^*}\right)^{1/4} \frac{1}{h_s^* r_o^*} \tag{11}$$

As a first order approximation, $A_d/A_{fb} = 1$ assumes that the upper half of the drop loses mass by diffusion while the lower half by film boiling.

The value of N_{DC} will be determined for water and various inert gases. These values will then be compared to the experimental results. In particular, for N_{DC} equal to zero there will be no diffusive evaporation, while for N_{DC} equal to or greater than 1 diffusive evaporation will dominate. For example, a water drop evaporating in a steam atmosphere would have a value of N_{DC} equal to zero.

In expressing W_d in the form given by equation (4), the partial pressure of the liquid in the vapor was assumed to be small in comparison to the saturation pressure of the liquid. In the actual situation, however, W_d is proportional to the difference between the two partial pressures:

$$W_d \propto P_s - P_\infty \tag{12}$$

To evaluate $(P_s - P_\infty)$, two idealized models could be used.

First, as illustrated in figure 1(a), the saturated vapor could rise up from beneath the drop, cover the upper surface of the drop, and to a great measure restrict the diffusion process from the top of the drop. In this case, P_∞ would approach the value of P_s. On the other hand, as suggested by Bell (ref. 5), two distinct flow regions could exist about the drop, as shown in figure 1(b). A saturated vapor region could form around the edges of the drop (region 1) while the surrounding inert gas could form a free convection cell about the top of the drop. In this case,

$$P_\infty << P_s \tag{13}$$

and the functional form of equation (4) for W_d would be completely justified.

As mentioned in the INTRODUCTION of this paper, the two region model seem to represent the actual physical situation. Consequently, equation (13) is valid.

ENVIRONMENTAL EXPERIMENTS

To establish the validity of the assumptions that produced the equation for N_{DC} (eq. (11)), an experiment should be performed in which the diffusive evaporation is a significant percentage of the total mass evaporated. Figure 4 presents the computed (eq. (11)), values of the N_{DC} group for a water drop in an atmosphere of helium, nitrogen, argon, and air. Table II lists the values of D_{AB} used in the calculations.

As seen in figure 4, at a plate temperature of about 360° C, the ratio of diffusive evaporation from the top of the drop to conductive evaporation from the bottom of the drop should be about 10 percent in air for a water drop of about 0.7 cc. In other words $(1 + N_{DC})$ equals 1.1. The parameter $(1 + N_{DC})$ is plotted in figure 4 rather than N_{DC}, because the vaporization rate is proportional to $(1 + N_{DC})$, as seen in equation (7). For argon and nitrogen atmospheres $(1 + N_{DC})$ increases only by 1 or 2 percent relative to air. Consequently, the evaporation time of a water drop in argon or nitrogen will be nearly equal or slightly smaller than the evaporation time of the same drop in air.

On the other hand, as seen in figure 4, the evaporation time of a water drop in helium would be much smaller than in air because of the increase in mass diffusion removal from the top of the drop as indicated by the larger value of $(1 + N_{DC})$.

To verify the above predictions, water drops were evaporated in air, argon, helium, and a nitrogen atmosphere. The experiments were conducted in a large cylindrical tank 60 cm in diameter and 60 cm long. Dry gas was periodically fed into the tank to keep the moisture level down. In addition, the first data point taken for a drop in a completely dry environment was always repeated at the end of a data set to check that the moisture level had not inadvertently risen to a high level.

The results of the experiment are shown in figure 5, which plots total vaporization time over drop volume. Qualitatively, the experimental results agree with the theoretical predictions. The vaporization times of a water drop at a plate temperature of 360° C were predicted to be nearly the same for the air, argon, or nitrogen environment. Also, the vaporization time in helium is much smaller as predicted.

For example, the 25 percent higher value of $(1 + N_{DC})$ for helium is mirrored in the data by an approximately 30 percent decrease in the total vaporization time for a 0.7 cc drop.

In addition to the previous experiments, 1 cc water drops were evaporated on a stainless steel hot plate at 376° C in air and with a steam cover. The average total vaporization time in air was 352 seconds, while in the steam atmosphere it was 377 seconds. This 7 percent decrease in the vaporization time in air compares favorably to the calculated value of 1.08 for $(1 + N_{DC})$.

Equation (7) can also provide an additional check of the dimensionless group N_{DC}. First, note that the left side of equation (7) is independent of the atmosphere. Thus, if the expression of equation (7) for atmosphere No. 1 is divided by the expression for atmosphere No. 2, the resulting ratio is

$$S = \frac{\left(\frac{dV}{dt}\right)_1}{\left(\frac{dV}{dt}\right)_2} = \frac{1 + \left(N_{DC}\right)_1}{1 + \left(N_{DC}\right)_2} \tag{14}$$

The ratio S for nitrogen (No. 1) to helium (No. 2) was calculated to be 0.84 at 0.7 cc. The measured ratio of the slopes from figure 5 is 0.91. The ratio S for air (No. 1) to helium was calculated to be 0.82 while the measured value is 0.75, which is fair agreement.

CONCLUSIONS

Based on the two-region flow model, the dimensionless group

$$N_{DC} = \frac{H}{Sc}\left(\frac{Pr^3}{Gr\ H^*}\right)^{1/4} \frac{1}{h_s^* r_o^*}$$

gives the ratio of diffusive evaporation rate from the top of the drop in comparison to film boiling evaporation from the thin vapor gap beneath the drop. This group is in fair agreement with the experimental data.

REFERENCES

1. Temple-Pediani, R. W., "Fuel Drop Vaporization Under Pressure on a Hot Surface," Proceedings of the Institution of Mechanical Engineers, Vol. 184, Pt. 1, No. 38, 1969-70, pp. 677-696.
2. Sigalla, A., "The Cooling of Hot Steel Strip with Water Jets," Journal of the Iron and Steel Institute, Vol. 186, Pt. 1, May 1957, pp. 90-93.
3. McGinnis, F. K., III and Holman, J. P., "Individual Droplet Heat-Transfer Rates for Splattering on Hot Surfaces," International Journal of Heat and Mass Transfer, Vol. 12, No. 1, Jan. 1969, pp. 95-108.
4. Forslund, R. P. and Rohsenow, W. M., "Dispersed Flow Film Boiling," Journal of Heat Transfer, Vol. 90, No. 4, Nov. 1968, pp. 399-407.
5. Bell, K. J., "The Leidenfrost Phenomenon: A Survey," Chemical Engineering Progress Symposium Series, Vol. 63, No. 79, 1967, pp. 73-82.
6. Wachters, L. H. J., "Heat Transfer from a Hot Wall to Drops in a Spheroidal State," Doctoral Thesis, 1965, Technical University of Delft, The Netherlands.
7. Schoessow, G. J. and Baumeister, K. J., "Velocity Effects on Leidenfrost Boiling of Various Liquids," Proceedings of the 4th International Heat Transfer Conference, Versailles, France, Vol. V., 1970, B 3.11.
8. Gottfried, B. S., Lee, C. J., and Bell, K. J., "The Leidenfrost Phenomenon: Film Boiling of Liquid Droplets on a Flat Plate," International Journal of Heat and Mass Transfer, Vol. 9, Nov. 1966, pp. 1167-1188.
9. Baumeister, K. J., Hamill, T. D., and Schoessow, G. J., "A Generalized Correlation of Vaporization Times of Drops in Film Boiling on a Flat Plate," Proceedings of the Third International Heat Transfer Conference, AIChE, Vol. 4, 1966, pp. 66-73.

10. Baumeister, K. J., "Heat Transfer to Water Droplets on a Flat Plate in the Film Boiling Regime," Ph.D. Thesis, 1964, University of Florida, Gainesville, Fla.

11. Baumeister, K. J., Hamill, T. D., Schwartz, F. L., and Schoessow, G. J., "Film Boiling Heat Transfer to Water Drops on a Flat Plate," Chemical Engineering Progress Symposium Series, Vol. 62, No. 64, 1966, pp. 52-61.

12. Gottfried, B. S. and Bell, K. J., "Film Boiling of Spheroidal Droplets," Industrial Engineering and Chemistry Fundamentals, Vol. 5, No. 4, Nov. 1966, pp. 561-568.

13. Baumeister, K. J. and Schoessow, G. J., "Creeping Flow Solution of Leidenfrost Boiling with a Moving Surface," Chemical Engineering Progress Symposium Series, Vol. 65, No. 92, 1969, pp. 167-174.

14. Baumeister, K. J., Hendricks, R. C., and Hamill, T. D., "Metastable Leidenfrost States," TN D-3226, 1966, NASA, Cleveland, Ohio.

15. Hendricks, R. C. and Baumeister, K. J., "Heat Transfer and Levitation of a Sphere in Leidenfrost Boiling," TN D-5694, 1970, NASA, Cleveland, Ohio.

16. Gottfried, B. S., "The Evaporation of Small Drops on a Flat Plate in the Film Boiling Regime," Ph.D. Thesis, 1962, Case Inst. of Technology, Cleveland, Ohio.

17. Reid, R. C. and Sherwood, T. K., "The Properties of Gases and Liquids," 2nd ed., McGraw-Hill, New York, 1966.

TABLE I. - RADIUS AND CONDUCTIVE HEAT TRANSFER COEFFICIENT FOR DROPLET FILM BOILING

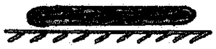
Dimensionless volume, $V^* = \frac{V}{L^3}$	Drop shape	Dimensionless radius, $r_o^* = \frac{r}{L}$	Dimensionless heat transfer coefficient, $h_s^* = \frac{h}{\frac{k}{L}(Gr\,Pr\,H^*)^{1/4}}$
$V^* \leq 0.8$	Small spheroid 	$r_o^* = \left(\frac{3V^*}{4\pi}\right)^{1/3}$	$h_s^* = 1.1\ V^{*-1/12}$
$0.8 < V^* \leq 155.$	Large drop 	$r_o^* = \left(\frac{1.25\ V^{*5/6}}{\pi}\right)^{1/2}$	$h_s^* = 1.075\ V^{*-1/6}$
$V^* > 155.$	Extended drop $\left\{\begin{matrix}\text{Constant}\\\text{thickness}\end{matrix}\right\}$ 	$r_o^* = \left(\frac{0.54\ V^*}{\pi}\right)^{1/2}$	$h_s^* = 1.64\ V^{*-1/4}$

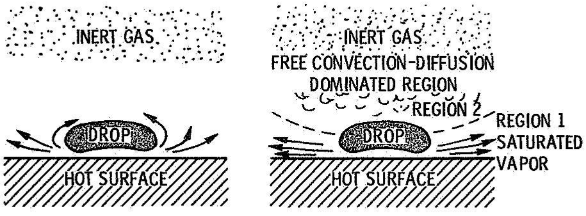
TABLE II. - DIFFUSION COEFFICIENTS (373 K AND ATMOSPHERIC PRESSURE)

Liquid-gas combination	D_{AB}, cm^2/sec	Reference	Comments
Water-air	0.353	16	---
Water-argon	0.41	17	(a)
Water-helium	1.22	17	(b)
Water-nitrogen	0.40	17	(b)

[a] D_{AB} calculated by Slattery-Bird equation corrected for water (eq. 11-27) as given in ref. 17.

[b] Experimental data given in table 11-4 of ref. 17 was linearly extrapolated to 373 K.

E-6268



(a) SATURATED ATMOSPHERE. (b) DISPERSED ATMOSPHERE.

Figure 1. - Velocity flow models for drops in film boiling.

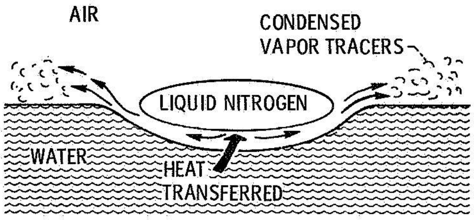
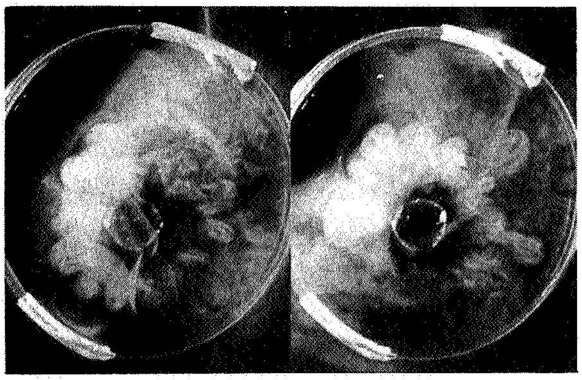
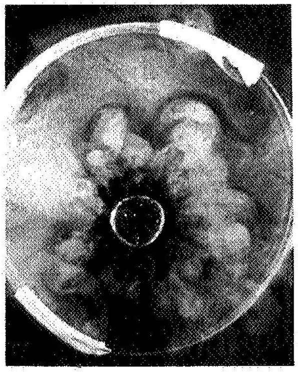


Figure 2. - Flow visualization technique.



Time increasing →



Time increasing →

Figure 3. - Photographs of vapor flow patterns for nitrogen drop on water.

E-6268

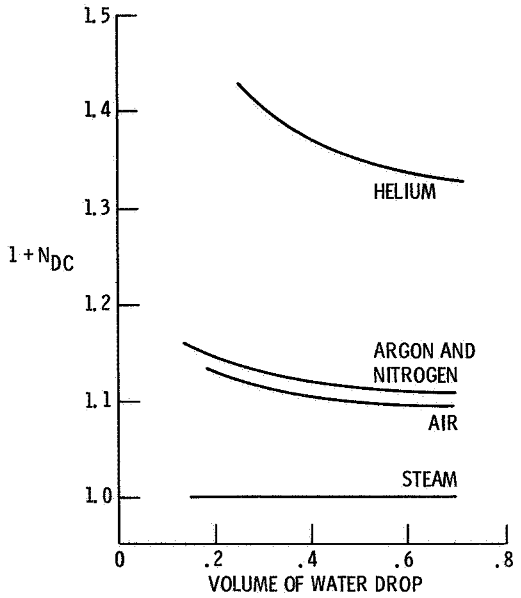


Figure 4. - Comparison of $(1 + N_{DC})$ for various water and inert gas combinations for atmospheric pressure and a plate temperature of about 360 C.

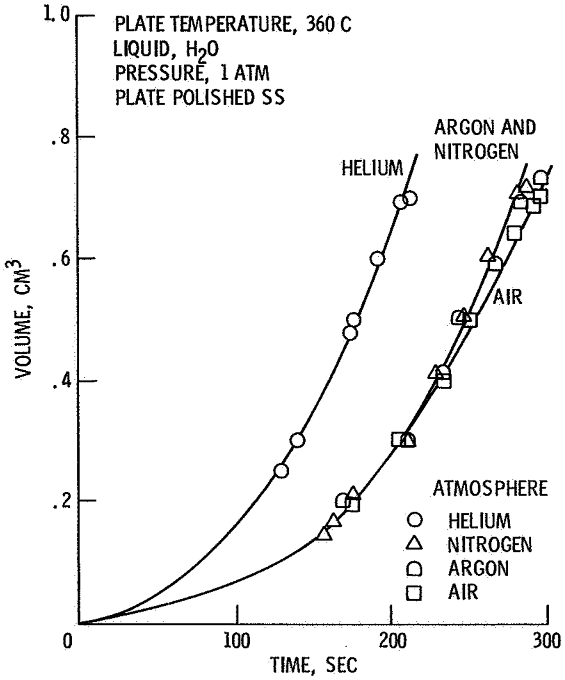


Figure 5. - Total vaporization data for various water and inert gas combinations.

NASA-Lewis