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TECHNICAL NOTE 2368

VAPORIZATION RATES AND HEAT-TRANSFER COEFFICIENTS FOR PURE LIQUID DROPS

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Cleveland, Ohio

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SUMMARY

This investigation to determine the vaporization rates of pure liquid drops vaporizing under conditions similar to those encountered in aircraft combustion systems uses the heat-balance equation

$$\frac{dm}{d\theta} = \frac{hA}{H_v} \Delta t$$

where $dm/d\theta$ is vaporization rate, h is heat-transfer coefficient, A area of drop, H_v latent heat of vaporization, and Δt is the driving force and is taken as the difference between the air temperature and the surface or wet-bulb temperature of the drop. Sensible heat transferred from the liquid was negligible in comparison with latent-heat requirements.

Nine liquids having latent-heat values from 50 to 500 gram-calories per gram were tested for an air-temperature range of 30° to 500° C and experimental values of the heat-transfer coefficient were correlated to give the expression

$$\frac{hd}{k_a} = \left(\frac{k_a}{k_v}\right)^{0.5} \left[2 + 0.303\ (\mathrm{Re\ Sc})^{0.6}\right]$$

where d is drop or sphere diameter, k_a is thermal conductivity of air evaluated at average film temperature, k_v is thermal conductivity of the vapor evaluated at average film temperature, Re is Reynolds number based on drop diameter d, and Sc is Schmidt group based on mass diffusivity of vapor. This expression was substituted for the heat-transfer coefficient in the heat-balance expression to obtain the final vaporization-rate equation

PERMANENT RECORD

$$\frac{dm}{d\theta} = \frac{k_a \Delta t}{H_v} \pi d \left(\frac{k_a}{k_v}\right)^{0.5} \left[2 + 0.303 \, (Re \, Sc)^{0.6}\right]$$

Vaporization rates at room temperatures experimentally determined in this investigation agreed with those calculated by mass-transfer equations, which use the difference between the partial pressures of the vapor at the drop surface and the vapor in the streaming air as the driving potential, but prediction of vaporization rates at elevated air temperatures required the use of the heat-balance equation. 2138

INTRODUCTION

The design of high-output combustors for jet-propelled aircraft and equipment such as spray dryers and cooling towers requires an accurate knowledge of liquid vaporization rates. The liquid may evaporate from spheres, cylinders, or flat surfaces depending on the type of equipment. In jet engines, the fuel is frequently injected as liquid droplets at a point upstream of the combustion zone, and the concentration of vaporized fuel in the fuel-air stream entering this zone is determined by the rate of vaporization of the droplets. In order to determine this rate, a study was made at NACA Lewis laboratory of droplets vaporizing under conditions similar to those encountered in aircraft combustion systems.

Two general methods may be used to calculate the vaporization rate of a pure liquid drop. Mass-transfer equations employ the difference between the partial pressure of the vapor at the drop surface and the partial pressure of the vapor in the streaming air as the driving potential. The other method is based on a heat-transfer equation and the driving potential is given as the difference between the air temperature and the surface temperature of the drop. An equation based on heat transfer as the controlling process and showing the effect of mass transfer on the heat-transfer coefficient was chosen for investigation.

In order to obtain a better understanding of the effect on vaporization of air temperature, a wetted cork sphere simulating a drop of liquid was placed in an air stream of constant mass-flow rate and varying temperature. Liquid was injected into the sphere at a rate equal to the vaporization rate, and the loss of liquid by vaporization from the sphere's surface was determined. The mass-flow rate of one liquid was varied to give values of Reynolds numbers from 1600 to 5700. Air temperatures were varied from 30° to 500° C in the tests of nine pure liquids having latent heats of vaporization ranging from 50 to 500 gram-calories per gram. The resulting data on vaporization rates were found to correlate with a semiempirical theory of heat and mass transfer. Surface-temperature data were obtained for each liquid and used in the corresponding heat-transfer calculations.

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SYMBOLS

The following symbols are used in the report:

A	area of drop, (sq cm)
$b_{g,w}$	molecular mass diffusivity $\left(\frac{PM}{RT_{av}} D_v\right)$, (g/(cm)(sec))
c_p	specific heat, (g-cal/(g)(°C))
D_v	volumetric diffusion coefficient or diffusivity, (sq cm/sec) (reference 5)
d	drop or sphere diameter, (cm)
$d(d)$	derivitive of drop diameter
$dm/d\theta$	vaporization rate, (g/sec)
f	proportionality constant
H_v	latent heat of vaporization, (g-cal/gram)
h	heat-transfer coefficient, (g-cal/(sec)(sq cm)(°C))
K	intercept constant, (°C)
k	thermal conductivity evaluated at t_{av}, (g-cal/(sec)(sq cm)(°C/cm))
M	molecular weight of diffusing vapor
m	quantity of material vaporized, (g)
Nu	Nusselt group for heat transfer, (hd/k)
Nu'	Nusselt group for mass transfer, $(K_m d/b_{g,w})$
P	total pressure, atmospheres
Pc	Peclet number, (Pr Re, $du\rho c/k$)
Pr	Prandtl number, $(\mu c/k)$
$p_{b,m}$	log mean pressure of inert or nondiffusing gas, (atmospheres)

p_v difference between partial pressure of vapor at drop surface (approximately saturation pressure) and partial pressure of vapor in streaming air, atmospheres

R Universal gas constant, 82.0 (atmospheres) (cu cm)/(^{o}K)(mole)

Re Reynolds number based on drop diameter d, ($du\rho/\mu$)

Re Sc new correlative group, ($du\rho/b_{g,w}$)

Sc Schmidt group based on mass diffusivity of vapor ($\mu/b_{g,w}$)

St Stanton number for heat transfer, ($h/\rho uc$)

St' Stanton number for mass transfer, ($K_m/\rho u$)

T temperature (^{o}K)

T_{av} average film temperature, (^{o}K)

t temperature, (^{o}C)

t_{av} average film temperature

$t_{a,l}$ air temperature at which liquid has same Δt value as water, (^{o}C)

$t_{a,w}$ air temperature at which water has same Δt value as given liquid, (^{o}C)

$t_{B.P.}$ boiling point of the liquid

Δt difference between air temperature and surface temperature of drop, (ta-ts) (^{o}C)

u velocity of air, (cm/sec)

θ vaporization time, (sec)

μ gas viscosity, (g/(sec)(cm))

π constant, (3.1416)

ρ gas density, (g/cu cm)

ρ_l liquid density, (g/cu cm)

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Subscripts:

a	air
l	liquid
o	initial condition
s	surface
v	vapor
w	water

Superscripts:

m,n,p	any exponent

PROCEDURE

The apparatus used to determine vaporization rates of pure liquid drops is shown in figure 1. Air was supplied from the central laboratory system at 50 pounds per square inch gage and 16-percent relative humidity. The air was metered by a rotameter, and the temperature was controlled over a range of 80° to 1000° F by an electric air heater. Air leaving the heater passed through an insulated 1-inch pipe and into a 3-inch-diameter calming chamber containing two sections of 200-mesh screen placed normal to the air stream. The calming section was used to produce an air stream with low turbulence and flat velocity profile. The velocity profile showed velocity variations of less than 10 percent for points within 1/4 inch of the wall of the test section. The sphere was placed at a depth of 1 inch from the open end and 1/2 inch from the wall of the 2-inch-diameter, 6-inch-long test section. The air temperature was measured by a thermocouple mounted in the same plane as the vaporization sphere.

The surface temperature of each liquid drop for the range of inlet temperature studied was obtained with a fine thermocouple junction of 40-gage iron-constantan wire flush with the surface of the sphere. An abbreviated technique of determining the surface temperature of each liquid drop for a given air temperature consisted in placing an iron-constantan thermocouple in the air stream, and ejecting liquid onto the thermocouple wire at a point 1 inch above the open end of the test section. Liquid flowed down the wire, formed a thin film around the thermocouple junction, and vaporized at the wet-bulb or surface temperature of the drop. A thermocouple element was also placed in the center of the sphere to determine the rate at which sensible heat of

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the liquid was transferred to the drop during the run, and to show the effect of the core temperature on the surface temperature of the drop.

The liquid feed system consisted of a syringe, hypodermic needle, and cork sphere mounted on the end of the hypodermic needle. Three spheres having an average diameter of 0.688 centimeter were used during the experiment. The spheres were constructed of selected cork free of coarse grains and piths, and the porosity of each was adjusted by piercing the sphere with a fine needle.

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Vaporization rates were measured directly by weighing the unit shown in figure 2 on an analytical balance before and after each vaporization run. The technique employed consisted in: (1) removing the test tube from the unit; (2) holding the sphere in the air stream for 2 minutes; and (3) replacing the test tube over the sphere. Results from the use of this equipment showed that vaporization data were reproducible within ±5 percent if the following conditions were fulfilled:

(1) Air temperatures varied less than 2° F

(2) A cork stopper was inserted in the open end of the test tube during the 2-minute vaporization run

(3) Pressure was applied evenly to the syringe and the unit was slowly rotated to keep the surface of the sphere thoroughly wet

(4) Not more than 1 second was taken to transfer the sphere from the test tube to the air stream or to accomplish the reverse procedure

Vaporization-rate data were taken at a constant inlet-air temperature of 28° C and varying air mass flow for a single liquid, and at constant air mass flow with air temperatures varying from 30° to 500° C for nine pure liquids. Surface-temperature data were taken over the same air temperature range for the nine liquids: nitrobenzene, n-octane, benzene, methanol, acetone, water, ethanol, butanol, and carbon tetrachloride.

The physical properties H_v, k, ρ, and μ that were used in the calculations were obtained from references 3 and 4.

RESULTS AND DISCUSSION

Analysis

The following equation of the mass-transfer type using partial pressures is given in reference 1 for calculating the vaporization rate of a pure liquid drop:

$$\frac{dm}{d\theta} = \frac{p_v MP}{RT\ p_{b,m}} D_v\ \pi d\ Nu'$$

$$Nu' = 2, \quad \text{when} \quad Re < 4$$

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$$Nu' = 1.50\ Sc^{1/3}\ Re^{0.35}, \quad \text{when} \quad 4 < Re < 400$$

$$Nu' = 0.43\ Sc^{1/3}\ Re^{0.56}, \quad \text{when} \quad Re > 400$$

Frössling (reference 2) presents the following mass-transfer equation

$$\frac{dm}{dO} = \frac{p_v M}{RT} \frac{P}{p_{b,m}} D_v\ d\ (2 + 0.552\ Sc^{1/3}\ Re^{1/2})$$

for all Reynolds number values and an air temperature of 20° C.

Consideration of the applicability of the mass-transfer equations in determining vaporization in high-temperature air streams shows that $p_{b,m}$ has a large effect on vaporization rates inasmuch as it varies markedly with small changes in the surface temperature of the drop. An accurate determination of surface temperatures is required in order to apply mass-transfer equations to vaporization calculations for high air temperatures. This evaluation becomes increasingly difficult as air temperatures are increased. For the second general method, however, the driving potential may be approximated by the difference between the air temperature and the boiling point of the liquid, and an accurate determination of the surface temperature is not required in the case of high air temperatures. An equation based on heat transfer as the controlling process and showing the effect of mass transfer on the film coefficient therefore was chosen for investigation.

A drop vaporizing in an air stream is shown in figure 3 as being surrounded by a vapor film. The heat balance for this system can be expressed

$$h' A\ (t_a - t_s) = \frac{dm}{d\theta} \left[H_v - c_p\ (t_l - t_s)\right] \tag{1}$$

where the heat-transfer coefficient h' is evaluated at the liquid-vapor interface. In this investigation, $c_p(t_l-t_s)$ is small compared with H_v, and the equation can be rewritten

$$h'A\ (t_a-t_s) = \frac{dm}{d\theta} H_v \tag{2}$$

When the heat-transfer coefficient h is evaluated at the vapor-air interface shown in figure 3, the heat balance may be written

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$$h'A\ (t_a-t_s) = \frac{dm}{d\theta} H_v \tag{3}$$

where the heat-transfer coefficient h' is a function of the heat transferred by the air and the diffusing vapor by collisions between vapor and air volecules. Three types of bimolecular collision may occur in a binary mixture of vapor and air surrounding the vaporizing drop. These types may be defined as collisions between: (1) two air molecules, (2) two vapor molecules, or (3) an air and a vapor molecule. When two air molecules collide, heat is transferred from the warmer molecule near the air stream to the cooler molecule that is closer to the sphere's surface. As a net result of collisions between air molecules, heat is conducted across the film to the surface of the sphere and can be expressed as a function of the thermal conductivity of air k_a. When two vapor molecules collide, this heat transfer, which may be expressed as a function of the thermal conductivity of the vapor k_v, has no appreciable effect on heat transferred to the sphere's surface because a net diffusion of vapor molecules into the air stream occurs. In collisions between air and vapor molecules, heat is transferred from the air to the vapor molecules, which conduct heat from the film as shown in figure 3. This heat transfer can be expressed as a function of the ratio k_a/k_v. The heat-transfer coefficient h may be expressed as a function of k_a and the thermal-conductivity ratio k_a/k_v.

Because the film coefficient for vaporization must be a function also of momentum- and mass-transfer groups, that is, the Reynolds and Schmidt numbers, it may be defined as

$$\frac{hd}{k_a} = f\left(\frac{k_a}{k_v}\right)^m (Re)^n(Sc)^p \tag{4}$$

where f is a proportionality constant.

Data for heat transfer between spheres and air have been correlated (reference 6), and the equation

$$\frac{hd}{k_a} = 0.33(Re)^{0.6} \tag{5}$$

obtained for a Reynolds number range of 20 to 150,000. This equation may be used to determine the effect of momentum transfer on heat transfer, but cannot be applied directly to vaporization because the simultaneous transfer of mass must be considered.

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Experimental Results

A series of runs was therefore made for one fluid in which mass-air-flow rates were varied and the air temperature was held constant, $((k_a/k_v)(Sc) = \text{constant})$. Data for these runs are given in table I and plotted in figure 4. This plot shows $n = 0.6$ or

$$\frac{hd}{k_a} = f\ (Re)^{0.6}\ (Sc)^p \left(\frac{k_a}{k_v}\right)^m \tag{6}$$

In equation (6), both Sc and k_a/k_v are functions of air temperature and the vapor properties. It is difficult, therefore, to vary either Sc or k_a/k_v independently as functions of the film coefficient. A correlation was undertaken using a new number Re Sc, which is defined as the ratio of turbulent momentum transfer to molecular mass transfer. This new correlative number is comparable to the Peclet number used in heat-transfer studies. The mutual relations existing between Re Sc and other dimensionless numbers are shown in figure 5.

By substituting $(Re\ Sc)^{0.6}$ for $(Re)^{0.6}\ (Sc)^p$, equation (6) can be rewritten

$$\frac{hd}{k_a} = f\ (Re\ Sc)^{0.6} \left(\frac{k_a}{k_v}\right)^m \tag{7}$$

because hd/k_a must still be a function of $Re^{0.6}$. In order to verify this relation and to evaluate m, vaporization tests were made in which the mass-air-flow rate was held constant and the air temperature was varied. Vaporization data for nitrobenzene, n-octane, benzene, methanol, acetone, water, ethanol, butanol, and carbon tetrachloride are given in table II; a logarithmic plot of $hd/k_a\ (Re\ Sc)^{0.6}$ against k_a/k_v for the nine liquids is shown in figure 6. From this straight-line plot, it is evident that $(Re\ Sc)^{0.6}$ correlates the data and $m = 0.5$; or

$$\frac{hd}{k_a} = f\ (\mathrm{Re\ Sc})^{0.6}\left(\frac{k_a}{k_v}\right)^{0.5} \tag{8}$$

The plot of $\dfrac{hd/k_a}{(k_a/k_v)^{0.5}}$ against $(\mathrm{Re\ Sc})^{0.6}$ presented in figure 7 shows that the equation for the heat-transfer coefficient of a pure liquid drop vaporizing in an air stream may be written 2138

$$\frac{hd}{k_a} = \left(\frac{k_a}{k_v}\right)^{0.5}\left[2 + 0.303\ (\mathrm{Re\ Sc})^{0.6}\right] \tag{9}$$

for the conditions covered in this investigation. The data in figure 7 show $hd/k_a = 2(k_a/k_v)^{0.5}$ for vaporization in quiescent air when the sphere diameter is greater than the mean free path of the molecules of the surrounding fluid.

Data were taken for various feed temperatures to check the effect of the sensible heat of the liquid on the vaporization rate, and the effect of feed temperatures on surface temperatures. The fact that no consistent trends of feed temperature were observed verified the assumption of negligible effect of the liquid feed temperature on the experimental heat-transfer coefficient.

When the value of h in equation (9) is substituted into the heat-balance equation (3), the vaporization rate of a pure liquid drop may be expressed

$$\frac{dm}{d\theta} = \frac{k_a \Delta t}{H_v}\pi d\left(\frac{k_a}{k_v}\right)^{0.5}\left[2 + 0.303\ (\mathrm{Re\ Sc})^{0.6}\right] \tag{10}$$

Surface temperatures measured in this experiment and shown as psychrometric plots in figure 8 were compared with wet-bulb temperatures given in reference 4 and were found to agree within 5 percent of these values for carbon tetrachloride, benzene, and water.

In order to compare values of $dm/d\theta$ obtained in this experiment with values calculated from equation (10), a plot of $dm/d\theta$ against air temperature for nitrobenzene is shown in figure 9. Values of

$dm/d\theta$ calculated by Frössling's equation are also shown in this figure, and agree fairly well with experimental data at room temperatures but are invalid at elevated air temperatures.

In order to determine the time required for a droplet of a given diameter to vaporize completely, equation (10) may be rewritten

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$$d\theta = \frac{\rho_l H_v}{4k_a \Delta t} \frac{d\, d(d)}{\left(\frac{k_a}{k_v}\right)^{0.5} \left[1 + 0.152 (\mathrm{Re\ Sc})^{0.6}\right]} \tag{11}$$

and integrated to give total vaporization time θ as a function of the initial diameter d_o; or

$$\theta = \frac{\rho_l H_v}{4k_a \Delta t} \frac{d_o^{1.4}}{0.213 \left(\frac{u\rho}{b_{g,w}}\right)^{0.6} \frac{k_a}{k_v}^{0.5}} \tag{12}$$

for values of $\mathrm{Nu} > 10$; and

$$\theta = \frac{\rho_l H_v}{4k_a \Delta t} \frac{d_o^2}{2\left(\frac{k_a}{k_v}\right)^{0.5}} \tag{13}$$

for values of $\mathrm{Nu} = 2(k_a/k_v)^{0.5}$.

A plot of equations (12) and (13) is shown in figure 10 for n-octane at $t_a = 680^\circ$ C, $u = 3050$ centimeters per second, and $\Delta t = 555^\circ$ C.

The applicability of equations (12) and (13) may be increased by approximating Δt from the boiling point of the liquid $t_{B.P.}$ by use of the equation

$$t_{a,w} = t_{a,l} - 0.80\, t_{B.P.} + 75 \tag{14}$$

and the plot in figure 8 of t_a against Δt of water. Thus, $\Delta t = (\Delta t)_w$, where $(\Delta t)_w$ is obtained from figure 8 at the value of $t_{a,w}$ calculated from equation (14). The derivation and application of this equation is discussed in the appendix.

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CONCLUSIONS

An analysis of the effect of elevated air temperatures on the rate of evaporation of a pure liquid drop based on a heat-balance concept resulted in the semiempirical equation:

$$\frac{dm}{d\theta} = \frac{k_a \, \Delta t}{H_v} \pi d \left(\frac{k_a}{k_v}\right)^{0.5} \left[2 + 0.303 \, (\mathrm{Re\ Sc})^{0.6}\right]$$

where $dm/d\theta$ is vaporization rate, k_a is thermal conductivity of air evaluated at average film temperature, t is the difference between air temperature and surface temperature of the drop, H is latent heat of vaporization, d is diameter of the drop, k_v is thermal conductivity of vapor at average film temperature, and Re Sc is the new correlative group.

An experimental verification over an air-temperature range of 30° to 500° C was obtained for 9 pure liquids having latent-heat values ranging from 50 to 500 gram-calories per gram.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, March 6, 1951.

APPENDIX - EVALUATION OF Δt BY BOILING POINT-METHOD

The applicability of equation (10)

$$\frac{dm}{d\theta} = \frac{k_a \, \Delta t}{H_v} \pi d \, Nu$$

may be considerably extended by approximating Δt from boiling-point
2138 data instead of relying on the availability of wet-bulb-temperature data. The psychrometric chart in figure 8 shows that Δt is a function of the boiling point of the liquid. A plot of $t_{a,l}$ against $t_{a,w}$ for constant Δt values was made, and is shown in figure 11.

The straight-line plot for each liquid is comparable to Dühring lines used in vapor-pressure determinations. The intercept of the ordinate axis $t_{a,w}$ was then evaluated as K and plotted against the boiling point of each liquid, as shown in figure 12.

The equations for the plots in figures 11 and 12 may be written

$$t'_{a,w} = t_{a,l} + K$$

and

$$K = -0.80 \, t_{B.P.} + 75$$

and may be combined to give the equation

$$t'_{a,w} = t_{a,l} - 0.80 \, t_{B.P.} + 75 \tag{14}$$

where $t_{B.P.} = 94^{\circ}$ C for the faired value of water.

This equation may be readily used to approximate the surface temperature of a drop from a plot of Δt against t_a for water if the air temperature and the boiling point of the liquid drop are known.

As an example of how one may determine Δt for a liquid having a boiling point of 80° C and suspended in a 250° C air stream, these values may be substituted in equation (14)

$$t_{a,w} = t_{a,l} - 0.80\ t_{B.P.} + 75$$

$$t_{a,w} = 250 - (0.80)(80) + 75 = 261^{\circ}\ C$$

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The plot of t_a against Δt for water in figure 8 shows that when $t_a = 261^{\circ}$ C, $\Delta t = 208^{\circ}$ C, which is the Δt value for a liquid having a boiling point of 80° C. As a check on the equation, the plot of benzene, which has a boiling point of 80° C, in figure 8 shows that $\Delta t = 206^{\circ}$ C in a 250° C air stream. For this condition, the method of determining Δt with equation (14) agrees with the experimental value within 1 percent.

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TABLE I - VAPORIZATION OF METHANOL FROM 0.688-CENTIMETER-DIAMETER SPHERE IN 28° C AIR STREAM OF VARYING MASS AIR-FLOW RATE

Vaporization rate (g/sec)	Air-flow rate (lb/hr)	Re	Nu
5.07×10^{-4}	75	1605	39.0
6.28	103	2240	48.4
7.32	132	2860	56.3
8.42	163	3540	64.8
9.10	196	4250	70.0
10.10	230	4980	77.6
11.30	263	5720	86.9

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TABLE II - VAPORIZATION FROM 0.688-CENTIMETER-DIAMETER

SPHERE AT CONSTANT MASS-AIR-FLOW RATES

t_a (°C)	Δt (°C)	Vaporization rate (g/sec)	Nu	$\frac{Nu}{(Re\ Sc)^{0.6}}$	$\frac{k_a}{k_v}$	$(Re\ Sc)^{0.6}$	$\frac{Nu}{(k_a/k_v)^{0.5}}$
Nitrobenzene-air; mass-air-flow rate, 94 lb/hr							
136	31	15.6×10^{-4}	27.0	0.450	1.96	60.0	19.3
152	40	19.2	25.0	.420	1.79	59.5	18.7
181	58	27.1	23.3	.398	1.66	58.5	18.1
207	77	40.8	24.8	.428	1.61	57.9	19.6
243	108	54.2	22.6	.394	1.53	57.4	18.3
258	121	63.1	22.8	.400	1.52	57.0	18.5
288	147	79.2	22.5	.400	1.44	56.3	18.8
302	159	82.8	21.5	.383	1.43	56.1	18.0
313	169	87.3	21.0	.382	1.42	55.0	17.6
377	224	126.5	20.9	.382	1.36	54.7	17.9
381	227	126.0	20.9	.382	1.33	54.7	18.1
403	246	134.0	19.7	.362	1.31	54.4	17.2
416	256	143.2	19.6	.362	1.30	54.1	17.2
427	267	155.3	20.0	.370	1.29	54.1	17.6
438	276	161.0	19.7	.367	1.28	53.7	17.4
507	336	209.0	19.3	.366	1.22	53.0	17.5
Water-air; mass-air-flow rate, 64 lb/hr							
27	17	1.2	33.0	0.389	1.42	84.8	27.7
43	27	2.1	35.1	.418	1.40	84.0	29.7
61	37	2.9	34.0	.414	1.38	82.1	28.9
76	49	3.6	30.9	.382	1.37	80.9	26.4
94	63	5.0	32.3	.398	1.35	81.2	27.8
110	77	6.0	31.0	.385	1.34	80.5	26.8
127	91	7.5	31.9	.400	1.33	79.8	27.7
160	120	10.4	32.0	.408	1.31	78.4	28.0
195	150	13.4	31.2	.402	1.30	77.6	27.4
213	166	14.9	30.6	.398	1.29	76.9	26.9
263	210	18.4	27.8	.369	1.27	75.3	24.7
282	228	19.1	25.9	.346	1.27	74.9	23.0
282	228	19.4	26.4	.352	1.27	75.0	23.4
406	345	32.2	25.0	.349	1.26	71.6	22.3
430	368	35.5	25.1	.352	1.24	71.3	22.5

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TABLE II - VAPORIZATION FROM 0.688-CENTIMETER-DIAMETER SPHERE AT CONSTANT MASS-AIR-FLOW RATES - Continued

n-Octane-air; mass-air-flow rate, 46.5 lb/hr							
t_a (°C)	Δt (°C)	Vaporization rate (g/sec)	Nu	$\frac{Nu}{(Re\ Sc)^{0.6}}$	$\frac{k_a}{k_v}$	$(Re\ Sc)^{0.6}$	$\frac{Nu}{(k_a/k_v)^{0.5}}$
31	10	4.0×10^{-4}	27.1	0.580	2.70	46.7	16.5
54	19	6.9	23.1	.504	2.45	45.8	14.8
61	22	9.2	26.0	.570	2.40	45.6	16.8
69	26	11.0	25.8	.568	2.33	45.4	16.9
83	35	14.8	24.8	.552	2.23	44.9	16.6
93	41	17.5	24.5	.548	2.17	44.7	16.6
92	40	17.5	25.1	.560	2.17	44.8	17.0
109	53	20.6	21.5	.485	2.09	44.3	14.9
116	58	24.4	22.9	.518	2.06	44.2	16.0
138	76	30.3	20.9	.478	1.95	43.7	15.0
184	115	45.9	19.5	.455	1.77	42.9	14.7
176	108	44.0	20.1	.467	1.80	43.0	15.0
202	130	51.0	18.5	.439	1.72	42.1	14.1
287	199	84.2	17.4	.423	1.51	41.1	14.2
291	202	86.0	17.4	.423	1.50	41.1	14.2
293	202	87.2	17.5	.425	1.50	41.2	14.3
294	206	87.2	17.1	.417	1.49	41.0	14.0
321	225	92.6	15.9	.391	1.44	40.7	13.3
325	228	95.2	16.0	.394	1.44	40.6	13.3
340	240	103.5	16.2	.401	1.41	40.4	13.6
356	253	110.8	16.1	.401	1.40	40.1	13.6
371	264	116.0	15.6	.391	1.37	39.9	13.3
397	285	125.7	15.3	.386	1.32	39.6	13.3
422	304	133.0	14.2	.362	1.32	39.2	12.4
435	315	137.5	13.9	.356	1.31	39.0	12.1

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TABLE II - VAPORIZATION FROM 0.688-CENTIMETER-DIAMETER SPHERE AT CONSTANT MASS-AIR-FLOW RATES - Continued

Benzene-air; mass-air-flow rate, 94 lb/hr

t_a (°C)	Δt (°C)	Vaporization rate (g/sec)	Nu	$\frac{Nu}{(Re\ Sc)^{0.6}}$	$\frac{k_a}{k_v}$	$(Re\ Sc)^{0.6}$	$\frac{Nu}{(k_a/k_v)^{0.5}}$
29	26	12.1×10^{-4}	39.3	0.480	2.46	81.9	25.1
39	32	15.1	38.8	.477	2.38	81.3	25.2
49	40	18.0	36.4	.452	2.31	80.5	29.0
65	52	22.9	34.5	.432	2.21	79.9	23.2
75	59	27.6	35.8	.452	2.16	79.2	24.4
83	65	29.6	34.3	.434	2.13	79.0	23.5
93	72	34.5	35.5	.453	2.06	78.4	24.7
108	84	41.8	35.8	.460	1.99	77.8	25.4
129	102	50.1	34.2	.444	1.89	77.0	24.9
131	104	52.4	35.0	.454	1.89	77.1	25.5
142	114	55.5	33.3	.434	1.87	76.7	24.4
158	127	65.4	34.1	.448	1.78	76.1	25.6
181	148	72.8	31.7	.419	1.70	75.7	24.3
173	140	66.4	30.9	.409	1.72	75.6	23.6
168	136	69.7	33.7	.444	1.74	75.9	25.6
173	140	67.7	31.5	.417	1.72	75.5	24.0
188	154	78.1	32.3	.430	1.68	75.1	24.9
207	170	86.7	31.6	.423	1.62	74.7	24.8
214	176	93.8	32.7	.439	1.61	74.5	25.8
226	186	95.3	30.8	.416	1.57	74.0	24.6
235	194	105.2	32.4	.437	1.55	73.7	25.9
258	214	114.5	30.7	.420	1.51	73.1	25.0
261	216	120.1	31.8	.436	1.50	72.9	26.0
278	230	123.7	29.9	.435	1.46	68.7	24.8
287	238	127.4	29.4	.407	1.45	72.2	24.4
298	248	138.8	30.3	.421	1.43	72.0	25.3
310	258	138.8	28.6	.400	1.41	71.5	24.1
321	268	150.1	29.4	.413	1.39	71.2	24.9

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TABLE II - VAPORIZATION FROM 0.688-CENTIMETER-DIAMETER

SPHERE AT CONSTANT MASS-AIR-FLOW RATES - Continued

t_a (°C)	Δt (°C)	Vaporization rate (g/sec)	Nu	$\frac{Nu}{(Re\ Sc)^{0.6}}$	$\frac{k_a}{k_v}$	$(Re\ Sc)^{0.6}$	$\frac{Nu}{(k_a/k_v)^{0.5}}$
Acetone-air; mass-air-flow rate, 75 lb/hr							
26	34	11.0×10^{-4}	35.5	0.465	2.36	76.3	23.1
68	68	21.9	32.9	.444	2.20	74.1	22.2
83	80	25.5	31.8	.434	2.14	73.3	21.7
102	95	34.1	34.7	.477	2.07	72.8	24.1
121	111	41.6	35.1	.487	2.01	72.1	24.8
134	122	49.6	37.2	.522	1.96	71.3	26.6
146	133	50.0	33.8	.476	1.93	71.0	24.3
168	153	60.8	34.6	.494	1.86	70.0	25.4
188	172	68.4	33.8	.485	1.81	69.7	25.1
204	187	74.8	33.2	.478	1.76	69.5	25.0
220	201	84.3	33.9	.492	1.72	68.9	25.9
234	215	89.7	33.0	.483	1.69	68.3	25.4
343	316	130.0	28.3	.430	1.48	65.8	23.3
346	318	124.0	26.7	.405	1.47	65.9	22.0
420	387	141.7	22.9	.357	1.41	64.2	19.3
Methanol-air; mass-air-flow rate, 75 lb/hr							
25	30	4.5	34.6	0.397	1.63	87.2	27.1
28	30	5.1	38.7	.444	1.63	87.2	30.3
41	42	6.5	34.6	.400	1.60	86.5	27.4
51	47	7.7	35.8	.419	1.57	85.4	28.6
60	55	8.6	33.6	.396	1.56	84.8	26.9
70	60	9.9	34.7	.412	1.55	84.2	27.9
83	72	12.1	34.8	.415	1.53	83.9	28.1
94	82	13.8	34.2	.410	1.51	83.4	27.8
104	91	15.2	33.4	.402	1.50	83.1	27.3
113	97	17.8	36.0	.436	1.48	82.6	29.6
126	109	18.2	32.2	.394	1.46	81.7	26.7
138	118	21.7	34.7	.425	1.45	81.6	28.8
154	132	23.2	32.4	.401	1.43	80.8	27.1
176	154	29.3	34.1	.425	1.40	80.2	28.8
196	172	34.2	34.6	.436	1.38	79.4	29.5
208	183	35.1	32.8	.415	1.36	79.0	28.1
122	105	18.0	32.9	.402	1.48	81.8	27.0
222	196	36.7	31.6	.402	1.34	78.6	27.3
208	183	34.6	32.4	.408	1.36	79.4	27.8
234	206	37.1	29.6	.378	1.33	78.3	25.7

TABLE II - VAPORIZATION FROM 0.688-CENTIMETER-DIAMETER

SPHERE AT CONSTANT MASS-AIR-FLOW RATES - Concluded

t_a (°C)	Δt (°C)	Vaporization rate (g/sec)	Nu	$\frac{Nu}{(Re\ Sc)^{0.6}}$	$\frac{k_a}{k_v}$	$(Re\ Sc)^{0.6}$	$\frac{Nu}{(k_a/k_v)^{0.5}}$
Ethanol air; mass-air-flow rate, 75 lb/hr							
26	20	4.1×10^{-4}	35.9	0.443	1.66	81.0	27.9
27	51	10.0	32.6	.410	1.60	79.5	25.8
97	74	14.7	30.8	.398	1.52	77.4	25.0
122	96	19.2	29.9	.391	1.50	76.5	24.4
149	120	23.1	27.5	.365	1.46	75.3	22.8
Butanol-air; mass-air-flow rate, 75 lb/hr							
108	56	14.8	27.6	0.405	1.63	68.1	21.6
149	89	23.5	25.6	.384	1.57	66.7	20.4
147	87	22.3	24.9	.372	1.57	66.9	19.9
177	114	34.6	28.2	.426	1.53	66.2	22.8
216	145	38.3	23.1	.355	1.46	65.1	19.1
Carbon tetrachloride-air; mass-air-flow rate, 75 lb/hr							
39	36	29.4	33.1	0.660	3.95	50.2	16.9
52	45	37.3	32.6	.655	3.89	49.8	16.7
63	52	42.9	30.5	.620	3.99	49.2	15.3
67	56	44.8	30.6	.621	3.83	49.3	15.6
77	62	52.7	31.8	.652	3.78	48.8	16.4
94	76	65.7	31.4	.648	3.72	48.5	16.3
97	78	66.7	30.8	.637	3.73	48.4	16.0
106	84	73.2	30.8	.642	3.70	48.0	16.0
117	95	85.3	31.2	.655	3.67	47.6	16.3

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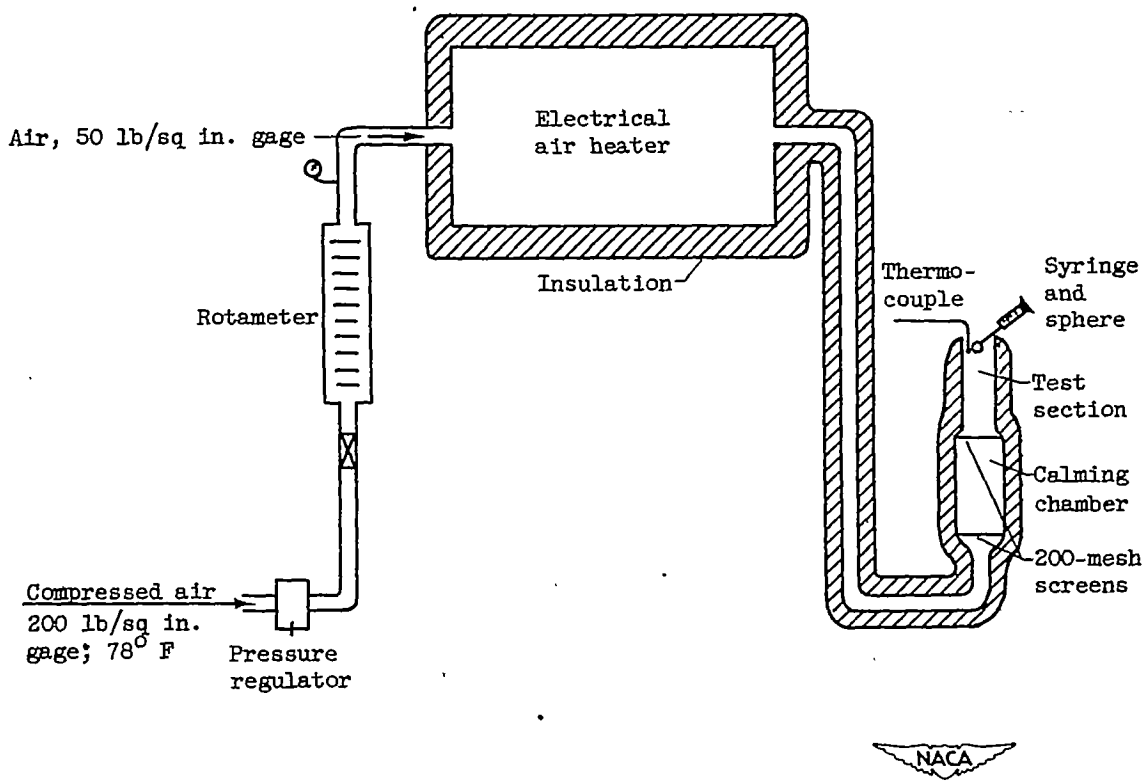

Figure 1. - Schematic diagram of vaporization equipment.

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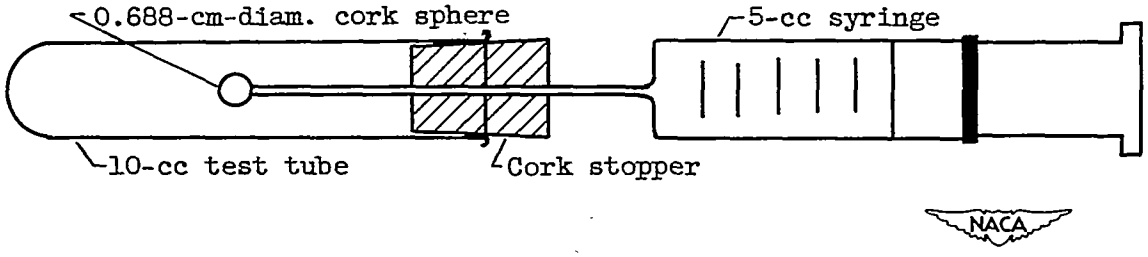

Figure 2. - Vaporization unit.

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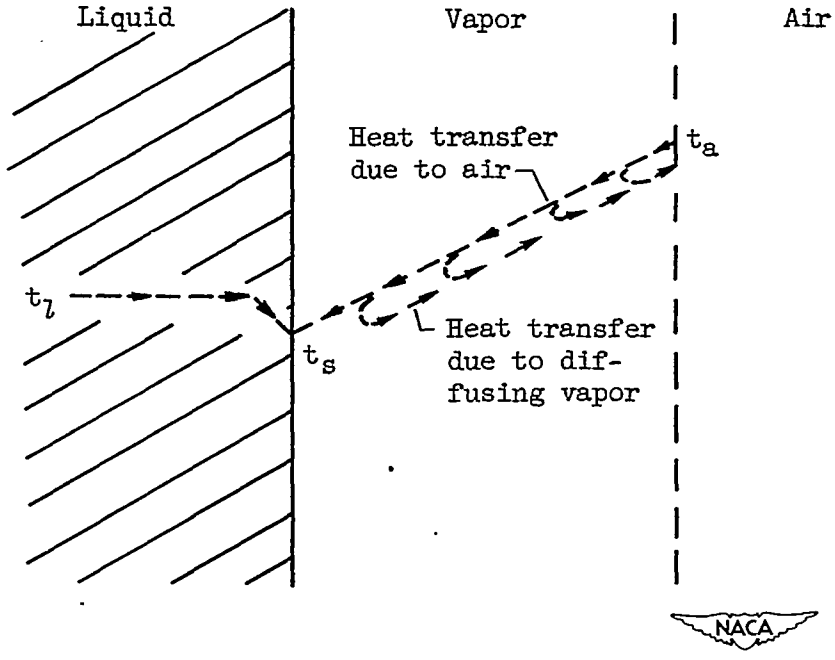

Figure 3. - Schematic representation of liquid drop vaporizing in air stream. (Arrows indicate direction of heat transfer.)

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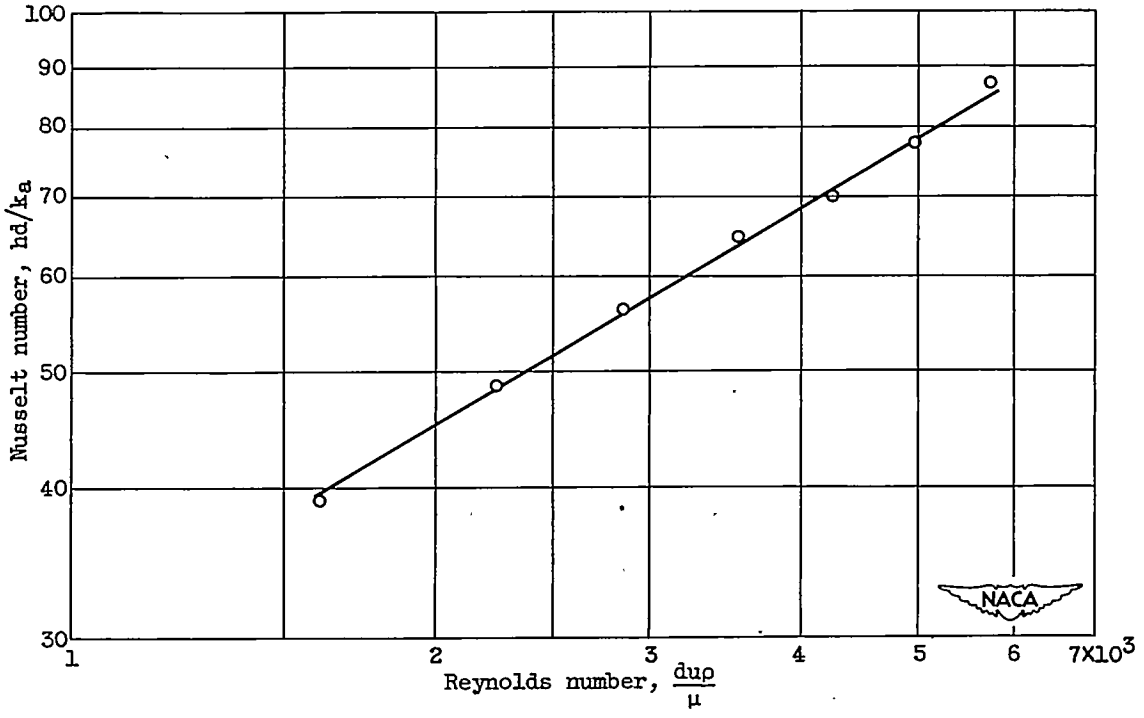

Figure 4. - Correlation of heat- and mass-transfer data for 0.688-centimeter-diameter methyl-alcohol drop in 28° C constant-temperature air stream, and variable air-mass-flow rate from 75 to 263 pounds per hour.

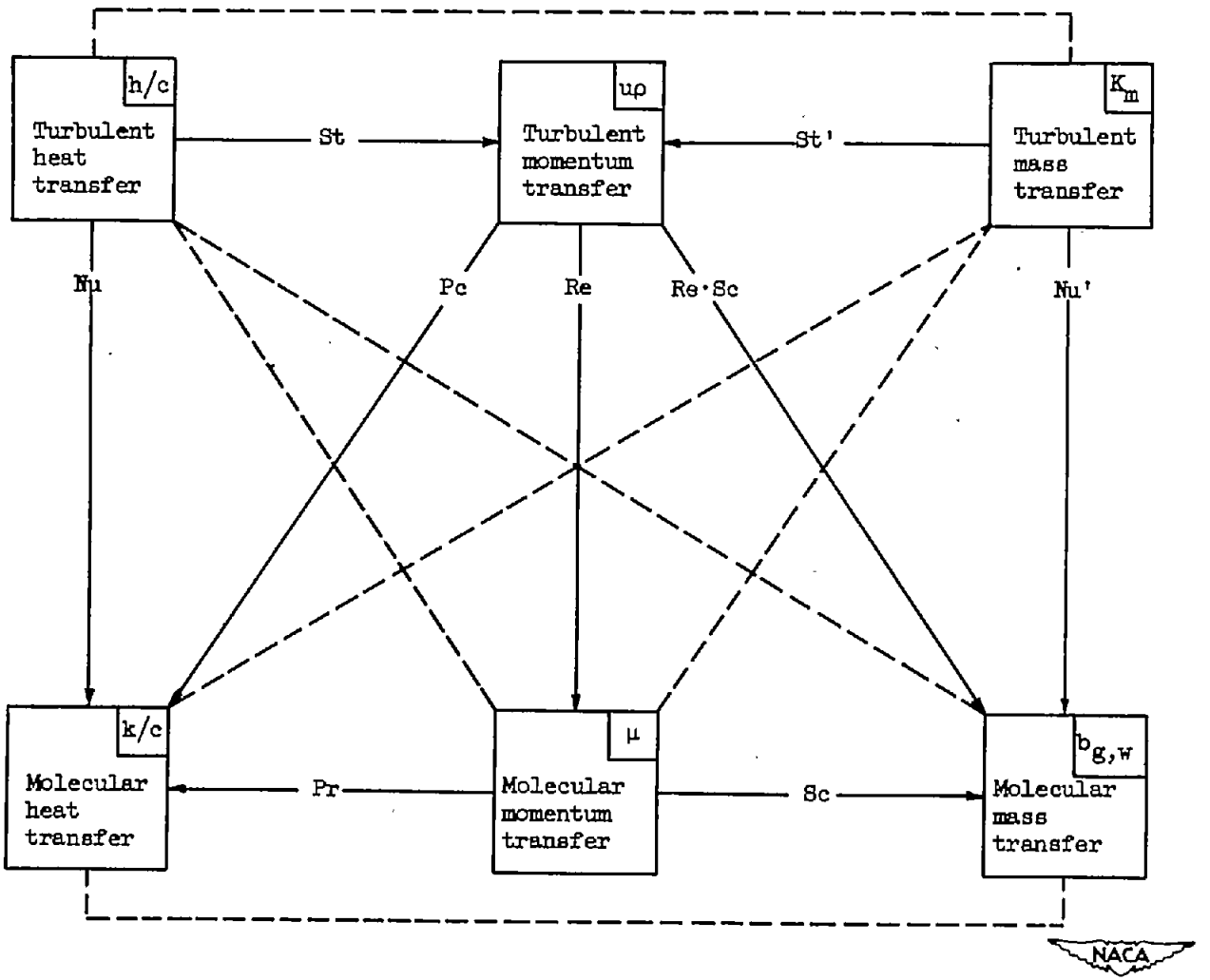

Figure 5. - Chart of dimensionless groups. Connecting arrows represent dimensionless groups and point from numerator to denominator for conventional appearance of the ratio.

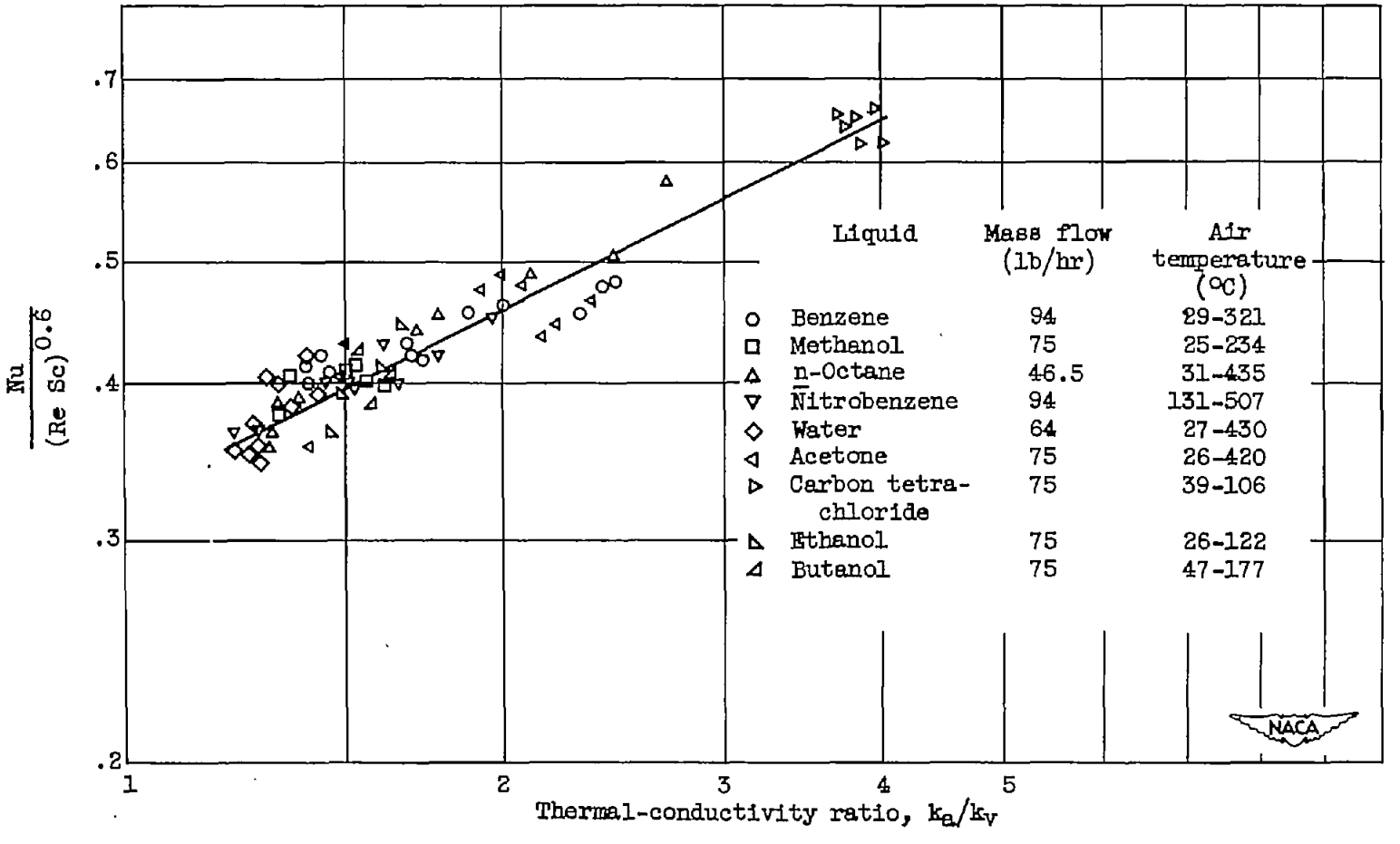

Figure 6. - Correlation of heat- and mass-transfer data with thermal conductivity ratio k_a/k_v.

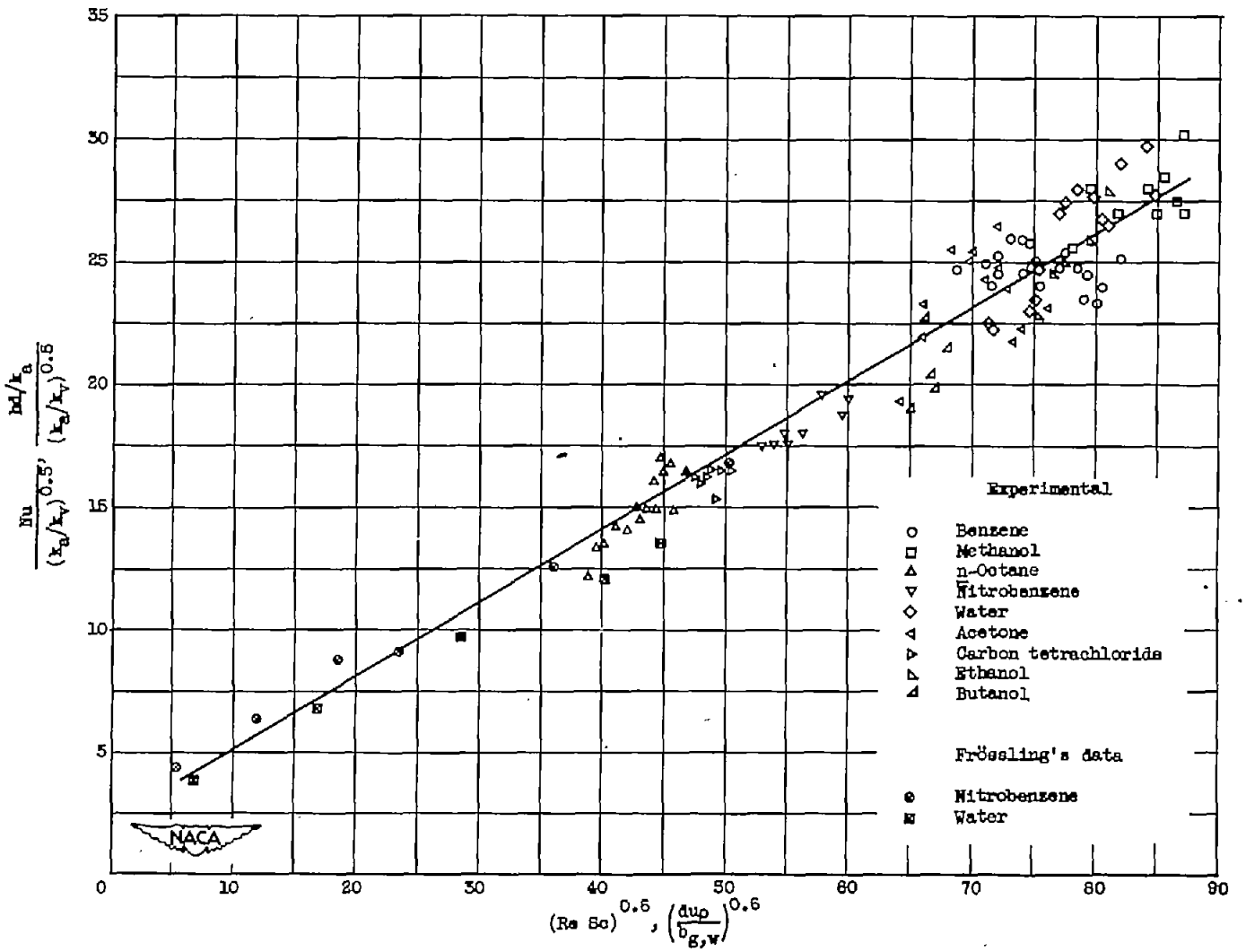

Figure 7. - Correlation of film coefficient h with thermal-conductivity ratio k_a/k_v and new correlative number (Re Sc).

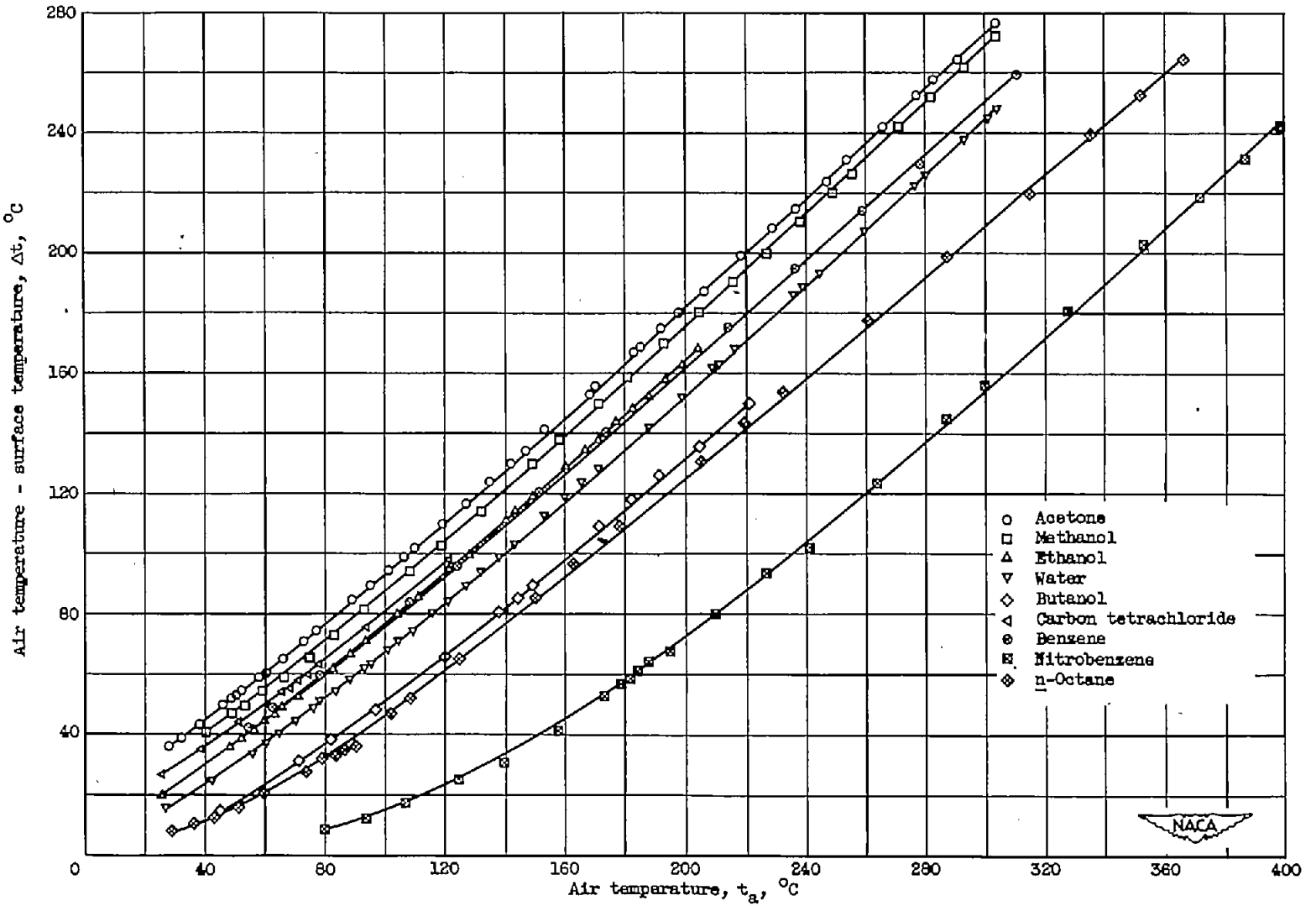

Figure 8. - Psychrometric plot of driving force Δt for nine pure liquids.

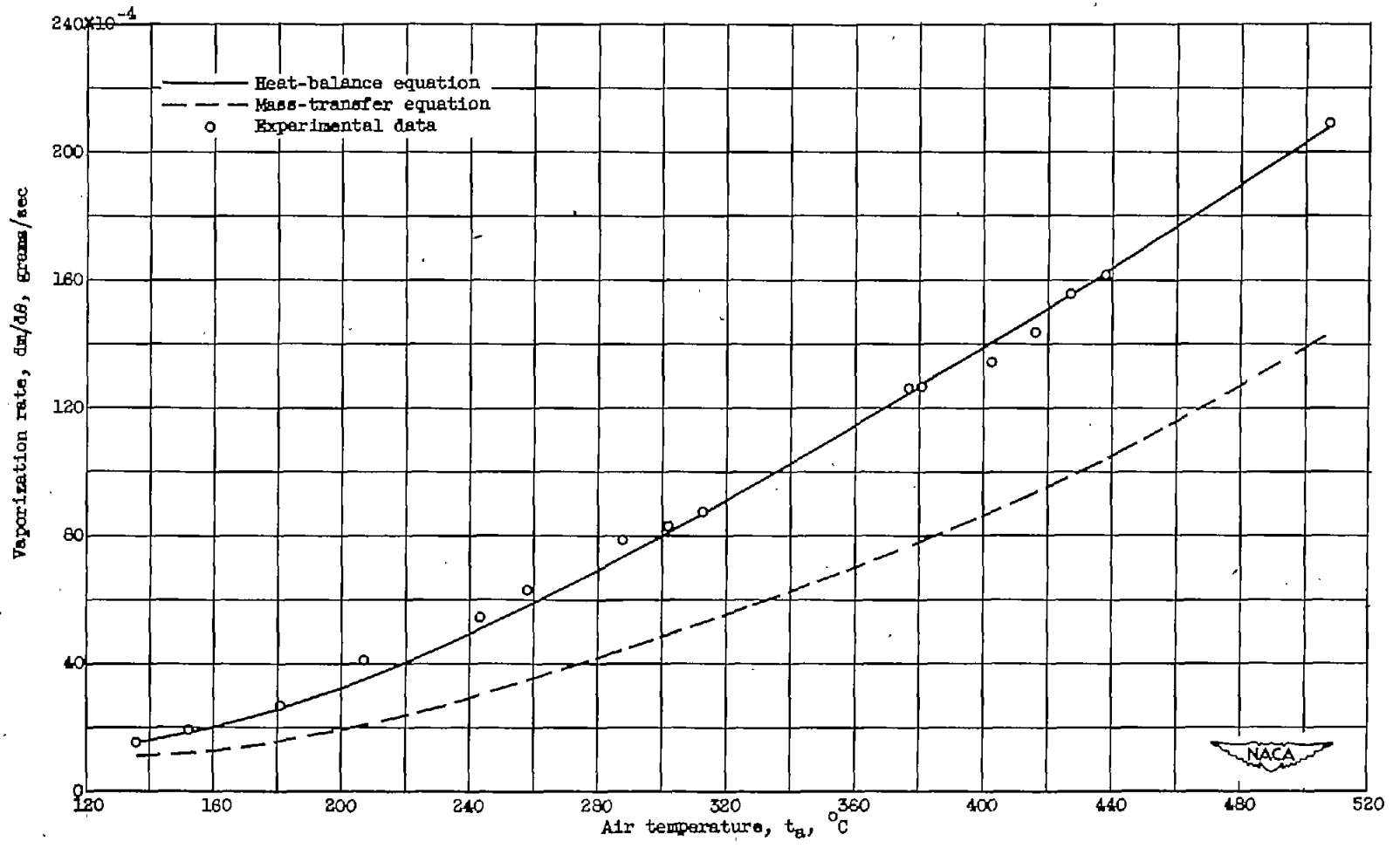

Figure 9. - Comparison of experimental vaporization rates for nitrobenzene drop in varying air temperature with rates calculated by heat-balance equation and mass-transfer equation (reference 2). Air-mass-flow rate, 94 pounds per hour; Reynolds number range, 1610 to 1030.

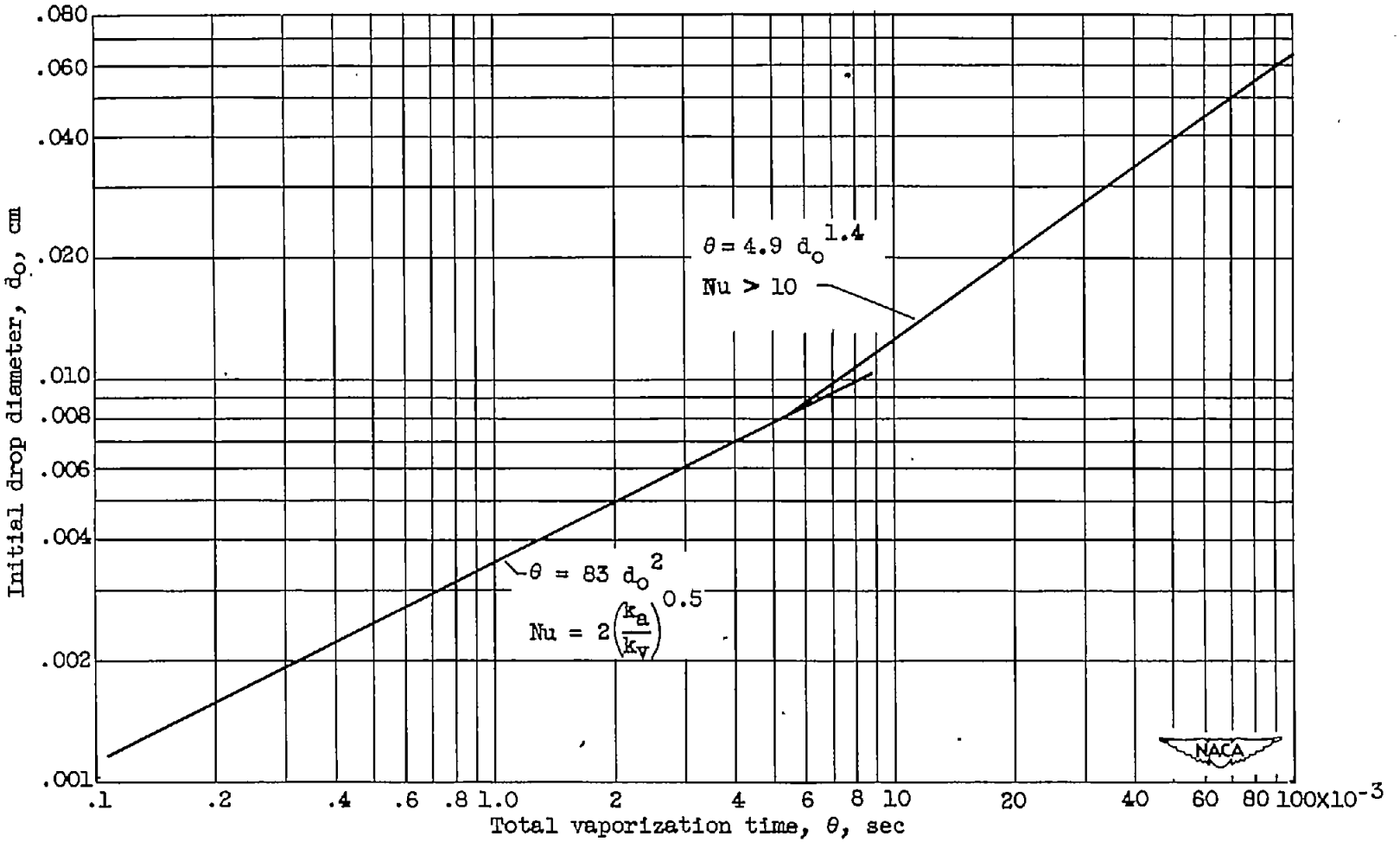

Figure 10. - Chart for determining vaporization time for n-octane droplet of initial droplet diameter, d_o. Conditions: $t_a = 680^\circ$ C; $u_a = 3050$ centimeters per second; $\Delta t = 555^\circ$ C.

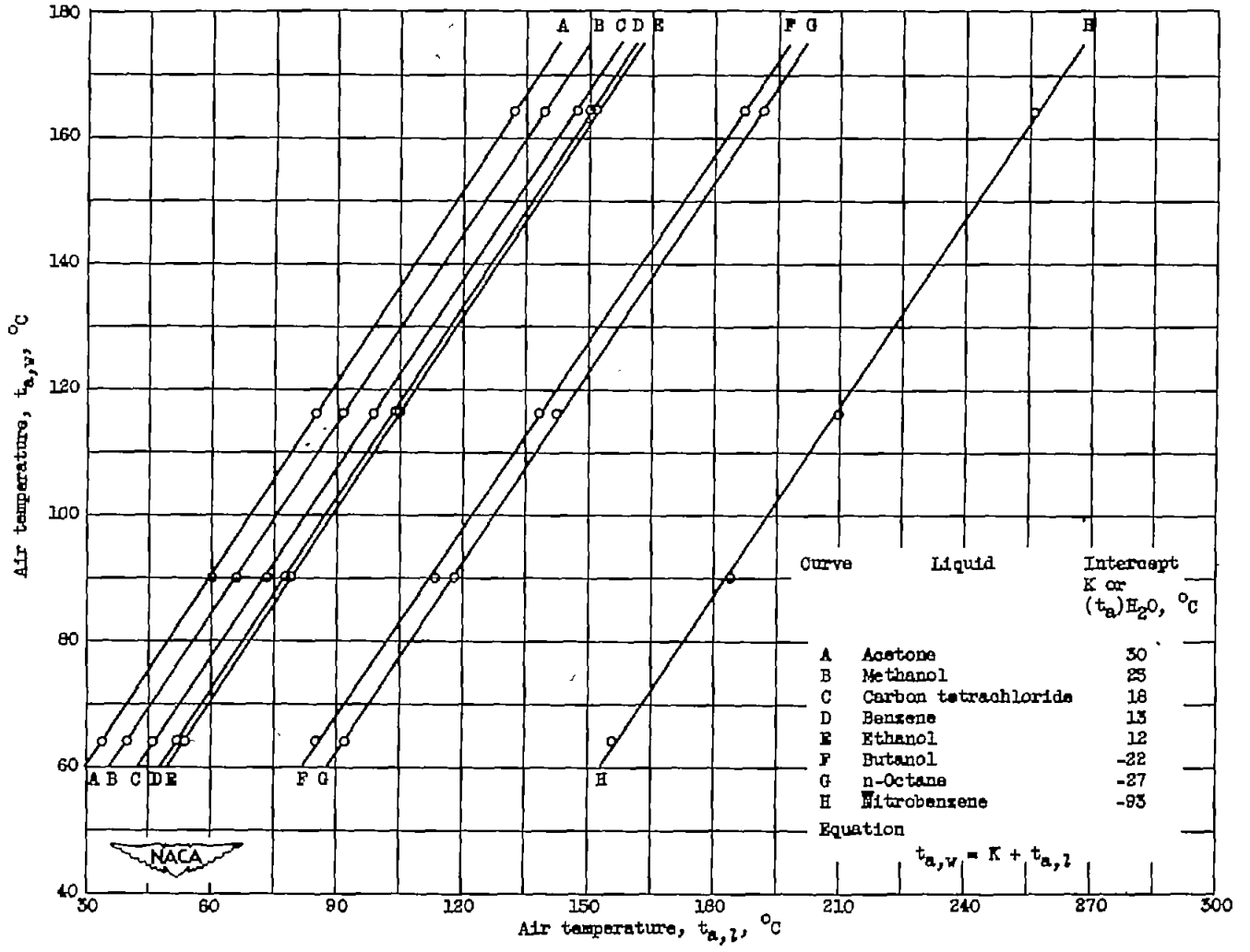

Figure 11. - Cross-plot of data of figure 8 to correlate values of air temperature $t_{a,w}$ that gives values of t_a-t_s with water equal to values of t_a-t_s obtained with other liquid at air temperatures $t_{a,l}$.

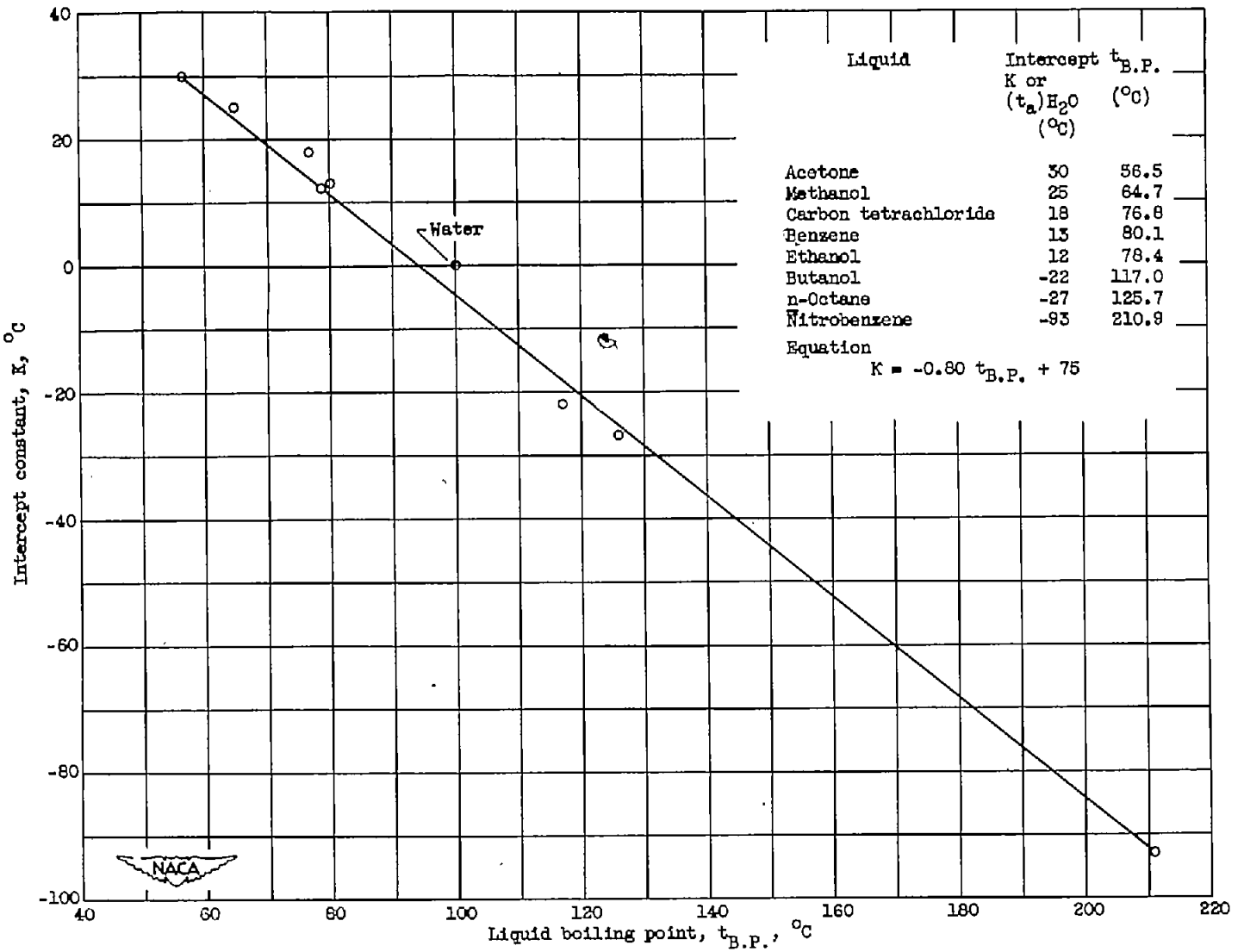

Figure 12. - Correlation of psychrometric data with boiling points.