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A SURVEY OF THE LITERATURE ON HEAT TRANSFER FROM SOLID SURFACES TO CRYOGENIC FLUIDS

BY

R. J. RICHARDS, W. G. STEWARD, R. B. JACOBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Technical Note

October 1961

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A SURVEY OF THE LITERATURE ON HEAT TRANSFER FROM SOLID SURFACES TO CRYOGENIC FLUIDS

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R. J. Richards, W. G. Steward, R. B. Jacobs
Cryogenic Engineering Laboratory
National Bureau of Standards
Boulder, Colorado

ABSTRACT

A bibliography of 156 references on heat transfer from solid surfaces to fluids and related phenomena is presented. Heat transfer data obtained from experimental work on cryogenic fluids are presented in graphical form. The theoretical and empirical formulations appearing in the references are presented. In those cases where sufficient information is available to make numerical computations, the formulations are presented graphically to permit comparison with the results of the experimental work.

CONTENTS

1. INTRODUCTION

Heat transfer problems confront investigators in nearly every branch of engineering. For cryogenic applications, it is necessary to have some knowledge of the whole field of heat transfer and specifically those aspects that are obviously applicable to low temperature systems.

The purpose of this note is to: (1) present a compilation of the recent (from 1940 to May 1960) experimental work dealing with heat transfer from solid surfaces to cryogenic fluids, (2) present a compilation of theoretical and empirical formulations for heat transfer to fluids in general, (3) compare and discuss (1) and (2), and determine areas which need further study. (Information on more recent work will appear in Advances in Cryogenic Engineering, Volume 6*)

Cryogenic heat transfer problems involve conduction, radiation, and convection with and without phase change. A large part of the available heat transfer literature is not directly concerned with cryogenic fluids but may be used with cryogenic systems. Therefore references which do not deal with cryogenic fluids, but may be applicable, are included here.

A document which summarizes all of the heat transfer information that may be of value to the solution of cryogenic problems would include most of the useful heat transfer literature. In order to define a manageable task the present survey is confined to information applicable to situations in which a cryogenic fluid is involved in the heat transfer mechanism.

The experimental data are presented in graphical form for liquid helium, liquid hydrogen, liquid oxygen and liquid nitrogen, the data for each liquid being plotted on one sheet.

For those cases where meaningful computations and comparisons can be made the theoretical and empirical formulations are also presented in the form of graphs which are readily comparable with the experimental graphs. Some discussion of these comparisons and some limitations of the equations used are given in section 4.

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* "Recent Advances in Cryogenic Engineering", Vol. 6, Plenum Press, Inc., New York, N. Y., 1961.

The references are listed alphabetically by author in the Bibliography (section 7). In section 6, the references are grouped according to those topics which (in our judgement) classify the material presented therein.

It is emphasized that this survey does not present the details of the work contained in the references, and the reader who is interested in these details (e.g., experimental techniques and theoretical derivations) must go to the original publication.

2. NOMENCLATURE

A	-	Area of heating surface, cm^2.
a	-	Thermal diffusivity, cm^2./sec.
c	-	Specific heat, joules/gram °K.
C	-	Constant.
d	-	Tube diameter, cm.
g	-	Acceleration due to gravity, cm./sec^2.
G	-	Mass velocity, grams/cm^2. sec.
Gr	-	Grashof number, $Gr = L^3 g\rho^2 \beta\Delta T/\mu^2$.
h	-	Film coefficient of heat transfer, watts/cm^2. °K.
J	-	Mechanical equivalent of heat, ergs/joule.
k	-	Thermal conductivity, watts/cm. °K.
L	-	Length of heating surface, cm.
Nu	-	Nusselt number, $Nu \equiv hL/k$ or $Nu \equiv hd/k$.
p	-	Pressure, dynes/cm^2.
p_a	-	Atmospheric pressure, dynes/cm^2.

Δp	-	Pressure difference corresponding to the temperature difference ΔT, dynes/cm^2.
Pr	-	Prandtl number, $Pr \equiv c_p \mu/k$.
$\dot{Q}$	-	Heat transfer rate, watts.
r	-	Radius, cm.
$\dot{r}$	-	Bubble velocity, cm./sec.
Re	-	Reynolds number, $Re \equiv \rho ud/\mu$ or $Re \equiv \rho uL/\mu$.
T	-	Temperature, °K.
ΔT	-	Temperature difference, °K$\Delta T \equiv T_w - T_{BL}$ for non-boiling liquid or surface boiling of subcooled liquids, $\Delta T \equiv T_w - T_s$ for boiling saturated liquids, $\Delta T \equiv T_w - T_v$ for heat transfer to vapor.
u	-	Velocity, cm./sec.
x	-	Mass fraction of vapor (quality).
β	-	Coefficient of thermal expansion, $(°K)^{-1}$.
λ	-	Latent heat of vaporization, joules/gram.
μ	-	Absolute viscosity, poise.
ν	-	Kinematic viscosity, cm^2/sec.
ρ	-	Density, grams/cm^3.
σ	-	Surface tension, dynes/cm.

Subscripts

av	-	average
b	-	bubble
BL	-	bulk liquid
g	-	gas
i	-	inside
L	-	liquid
max	-	maximum
o	-	outside
out	-	outlet of heater
p	-	pressure
s	-	saturation
v	-	vapor
w	-	wall

3. GRAPHICAL PRESENTATIONS

The following graphs present the experimental data found in the literature and the curves calculated by means of the theoretical and empirical formulations taken from the literature. The calculated graphs are transparent overlays so that they can be easily compared with the experimental data. Due to limited data on the properties of cryogenic fluids some of the calculated curves do not cover the range of the experimental data. Also some of the formulations neglect factors such as diameter and conditions of the heating surface; the experimental data show that these factors do affect the heat transfer.

3.1 Experimental Data

The experimental data found during this survey and dealing with helium, hydrogen, oxygen, and nitrogen are plotted in figures 2, 4, 6, and 8 respectively; the coordinates are heat flux versus temperature difference between the heating surface and the bulk of the fluid. The data, notations, etc. are reproduced as found in the literature. For example, only those nucleate boiling heat fluxes which the original author indicated as maxima are so identified on the graphs. Pertinent information such as system pressure, heater geometry and orientation, etc. are given on the figures. Both forced and natural convection data are included.

3.2 Theoretical and Empirical Formulations

The results obtained by applying the various theoretical and empirical formulations to helium, hydrogen, oxygen, and nitrogen are shown in figures 1, 3, 5, and 7 respectively. The formulations are discussed in section 4. Computations were performed for most of the formulation; however, for reasons given in section 4 it was either not possible or not desirable to perform computations with some of the formulations.

3.3 Comparison of Data with Formulations

Figures 1 through 8 are plotted so that the various theoretical and empirical formulations can be easily compared with corresponding experimental curves. In cases where geometrical factors, pressure, or other parameters are required in order to make a computation, the values chosen for these parameters are noted next to the computed curves. These curves should be compared only with the experimental curves having nearly the same values for these factors. The computed results are compared with the experimental data in section 4.

4. SUMMARY OF AVAILABLE THEORETICAL AND EMPIRICAL FORMULATIONS

This summary is not intended to replace original publications. The reader who is interested in detailed derivations, assumptions, experimental and analytical techniques, etc., must refer to the original papers.

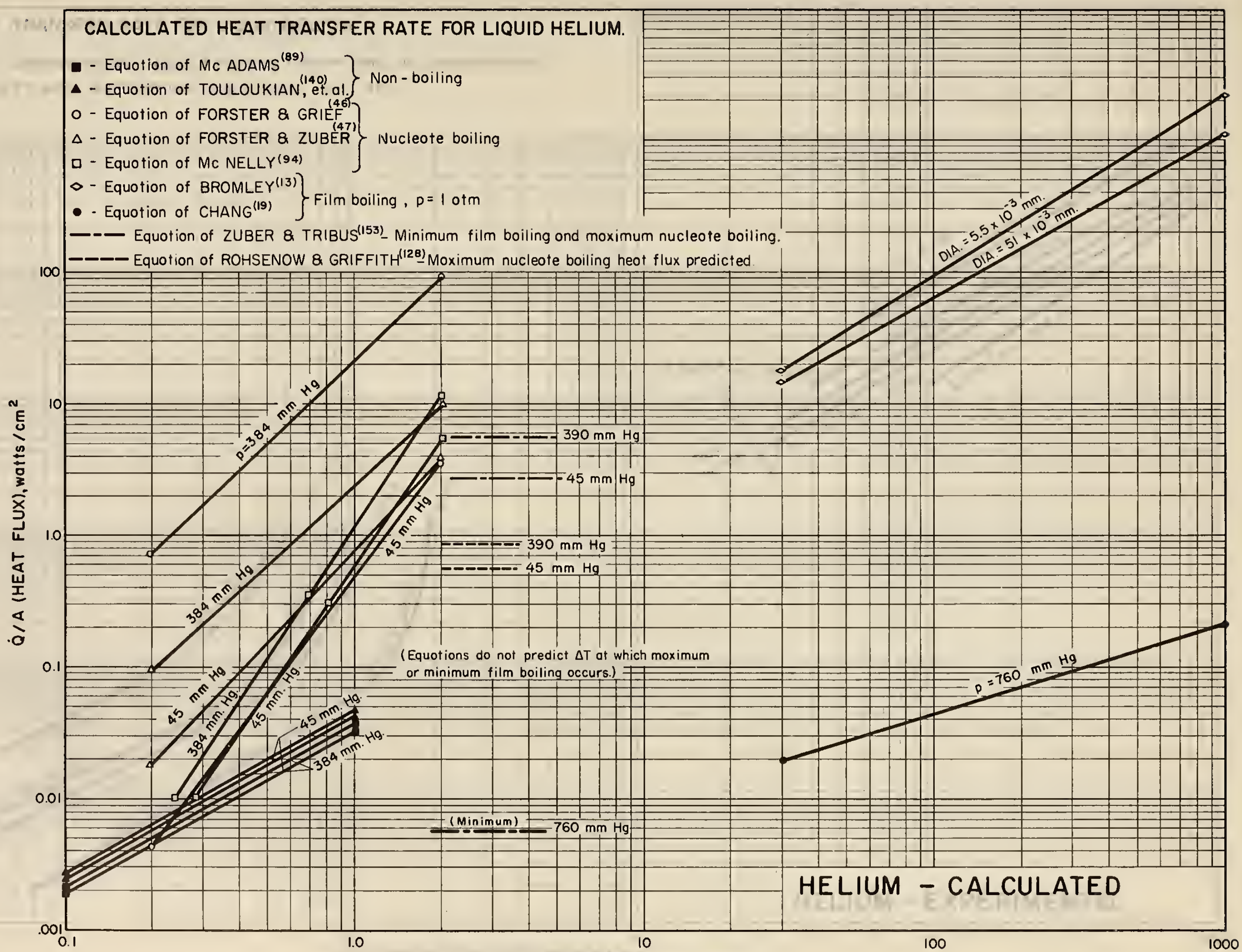
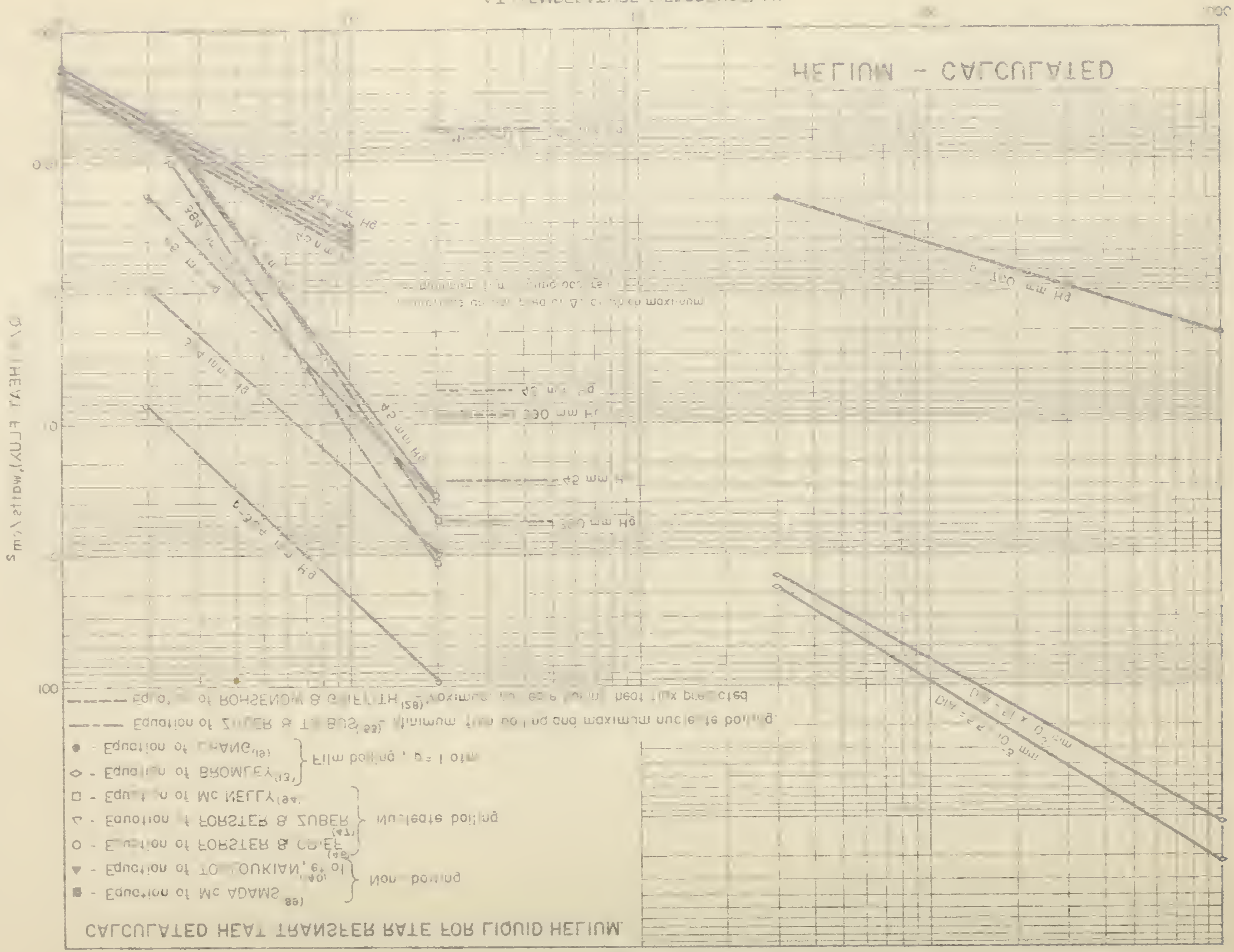
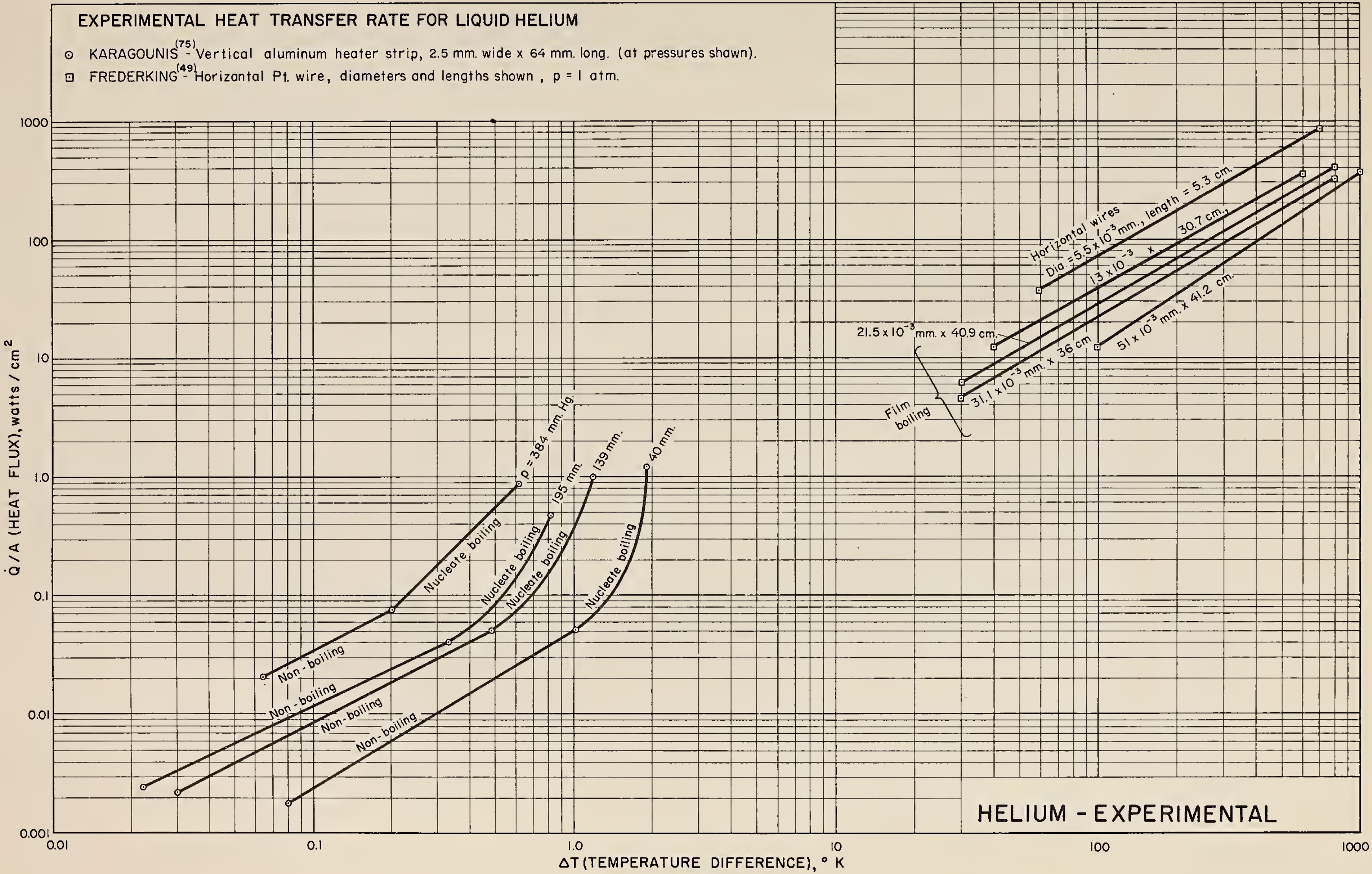

CALCULATED HEAT TRANSFER RATE FOR LIQUID HELIUM.
■ - Equation of Mc ADAMS(89)
▲ - Equation of TOULOUKIAN, et. al.(140)
Non - boiling
○ - Equation of FORSTER & GRIEF(46)
△ - Equation of FORSTER & ZUBER(47)
□ - Equation of Mc NELLY(94)
Nucleate boiling
◇ - Equation of BROMLEY(13)
● - Equation of CHANG(19)
Film boiling , p= 1 atm
Equation of ZUBER & TRIBUS(153) Minimum film boiling and maximum nucleate boiling.
Equation of ROHSENOW & GRIFFITH(128) Maximum nucleate boiling heat flux predicted
Q̇/A (HEAT FLUX), watts/cm²
100
10
1.0
0.1
0.01
.001
0.1
1.0
10
100
1000
p=384 mm Hg
384 mm Hg
45 mm Hg
384 mm. Hg.
45 mm. Hg.
45 mm Hg
45 mm. Hg.
384 mm. Hg.
390 mm Hg
45 mm Hg
390 mm Hg
45 mm Hg
(Equations do not predict ΔT at which maximum or minimum film boiling occurs.)
(Minimum)
760 mm Hg
DIA. = 5.5 x 10⁻³ mm.
DIA. = 51 x 10⁻³ mm.
p = 760 mm Hg
HELIUM - CALCULATED
ΔT (TEMPERATURE DIFFERENCE), °K

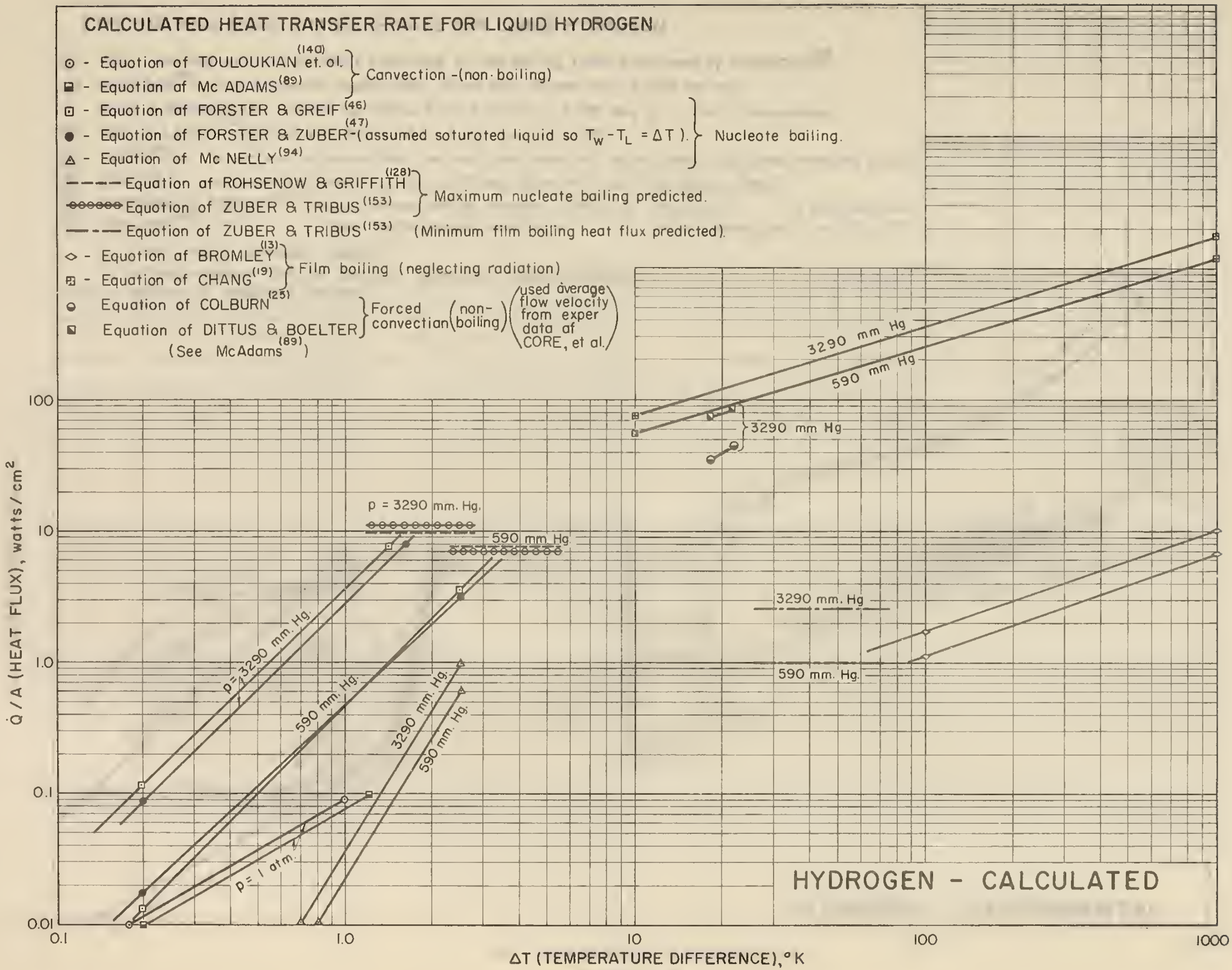
FIGURE 1

FIGURE



ΔT (TEMPERATURE DIFFERENCE), °K
Q/A (HEAT FLUX), watts/cm²
HELIUM - CALCULATED
45 mm Hg
390 mm Hg
760 mm Hg
CALCULATED HEAT TRANSFER RATE FOR LIQUID HELIUM.
Equation of ROHSENOW & GRIFFITH (26), maximum nucleate boiling heat flux predicted
Equation of ZUBER & TRIBUS (53), Minimum film boiling and maximum nucleate boiling
Equation of CHANG (18)
Equation of BROMLEY (13)
Film boiling, p = 1 atm
Equation of Mc NELLY (84)
Equation of FORSTER & ZUBER
Equation of FORSTER & GREIF (47)
Nucleate boiling
Non - boiling
Equation of Mc ADAMS (88)


EXPERIMENTAL HEAT TRANSFER RATE FOR LIQUID HELIUM
⊙ KARAGOUNIS(75) - Vertical aluminum heater strip, 2.5 mm. wide x 64 mm. long. (at pressures shown).
⊡ FREDERKING(49) - Horizontal Pt. wire, diameters and lengths shown, p = 1 atm.
1000
100
10
1.0
0.1
0.01
0.001
Q̇/A (HEAT FLUX), watts / cm²
0.01
0.1
1.0
10
100
1000
p = 384 mm. Hg.
195 mm.
139 mm.
40 mm.
Nucleate boiling
Nucleate boiling
Nucleate boiling
Nucleate boiling
Non - boiling
Non - boiling
Non - boiling
Non - boiling
Horizontal wires
Dia. = 5.5 x 10⁻³ mm., length = 5.3 cm.
13 x 10⁻³ x 30.7 cm.
21.5 x 10⁻³ mm. x 40.9 cm.
31.1 x 10⁻³ mm. x 36 cm
51 x 10⁻³ mm. x 41.2 cm.
Film boiling
HELIUM - EXPERIMENTAL
ΔT (TEMPERATURE DIFFERENCE), ° K
FIGURE 2



CALCULATED HEAT TRANSFER RATE FOR LIQUID HYDROGEN
Equotion of TOULOUKIAN et. ol. (140)
Equotian of Mc ADAMS (89)
Canvection -(non-boiling)
Equotion of FORSTER & GREIF (46)
Equotion of FORSTER & ZUBER (47) -(assumed soturoted liquid so T_W - T_L = ΔT).
Nucleote boiling.
Equotion of Mc NELLY (94)
Equation of ROHSENOW & GRIFFITH (128)
Equotion of ZUBER & TRIBUS (153)
Maximum nucleate bailing predicted.
Equotion of ZUBER & TRIBUS (153)
(Minimum film boiling heat flux predicted).
Equotion of BROMLEY (13)
Equotion of CHANG (19)
Film boiling (neglecting radiation)
Equotion of COLBURN (25)
Equotion of DITTUS & BOELTER
(See McAdams (89))
Forced convectian
(non-boiling)
(used average flow velocity from exper data af CORE, et al.)
3290 mm Hg
590 mm Hg
3290 mm Hg
p = 3290 mm. Hg.
590 mm Hg
3290 mm. Hg
590 mm. Hg.
p=3290 mm. Hg.
590 mm. Hg.
3290 mm. Hg.
590 mm. Hg.
p=1 atm.
HYDROGEN - CALCULATED
Q̇ / A (HEAT FLUX), watts / cm²
ΔT (TEMPERATURE DIFFERENCE), °K
0.01
0.1
1.0
10
100
1000

FIGURE 3

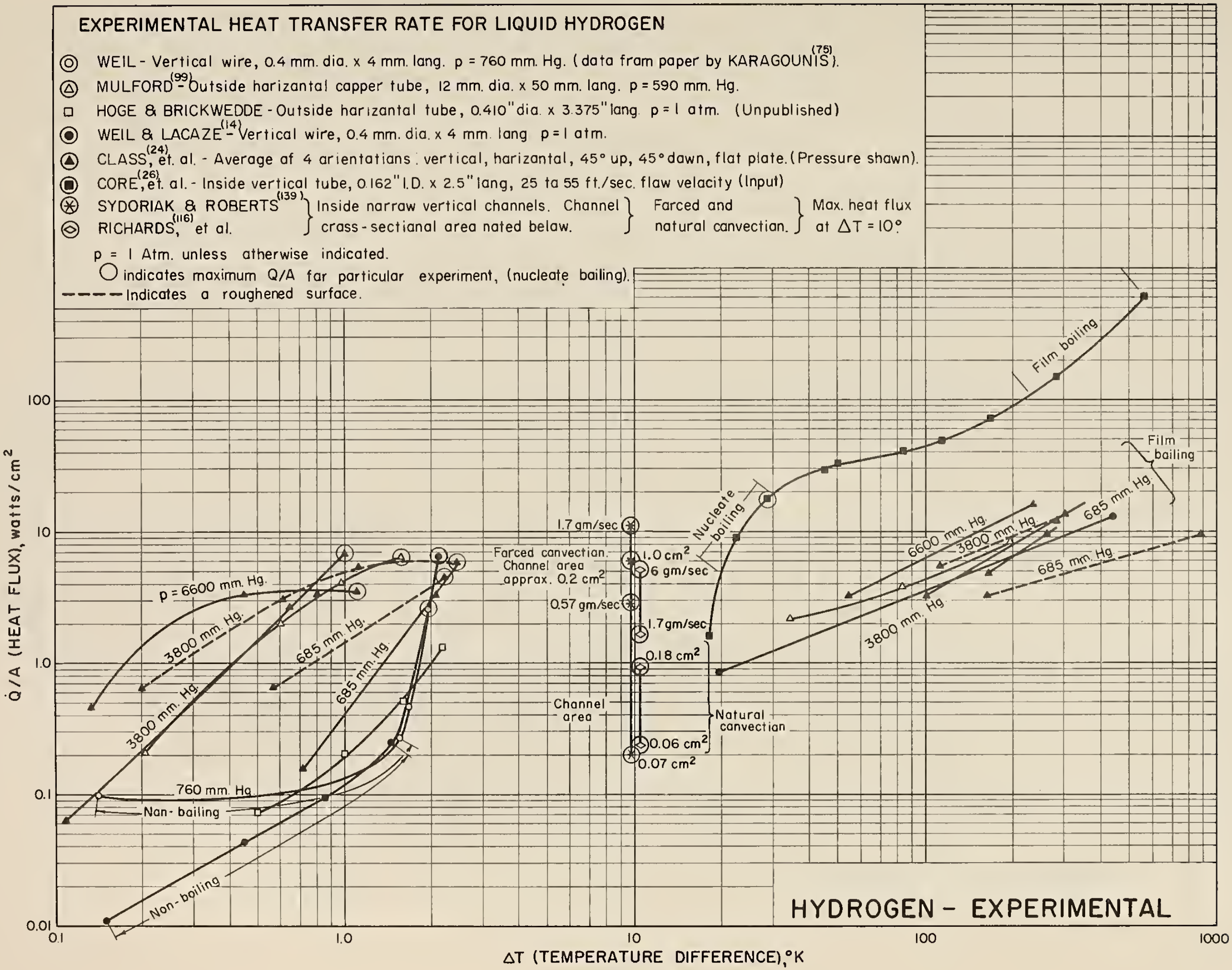
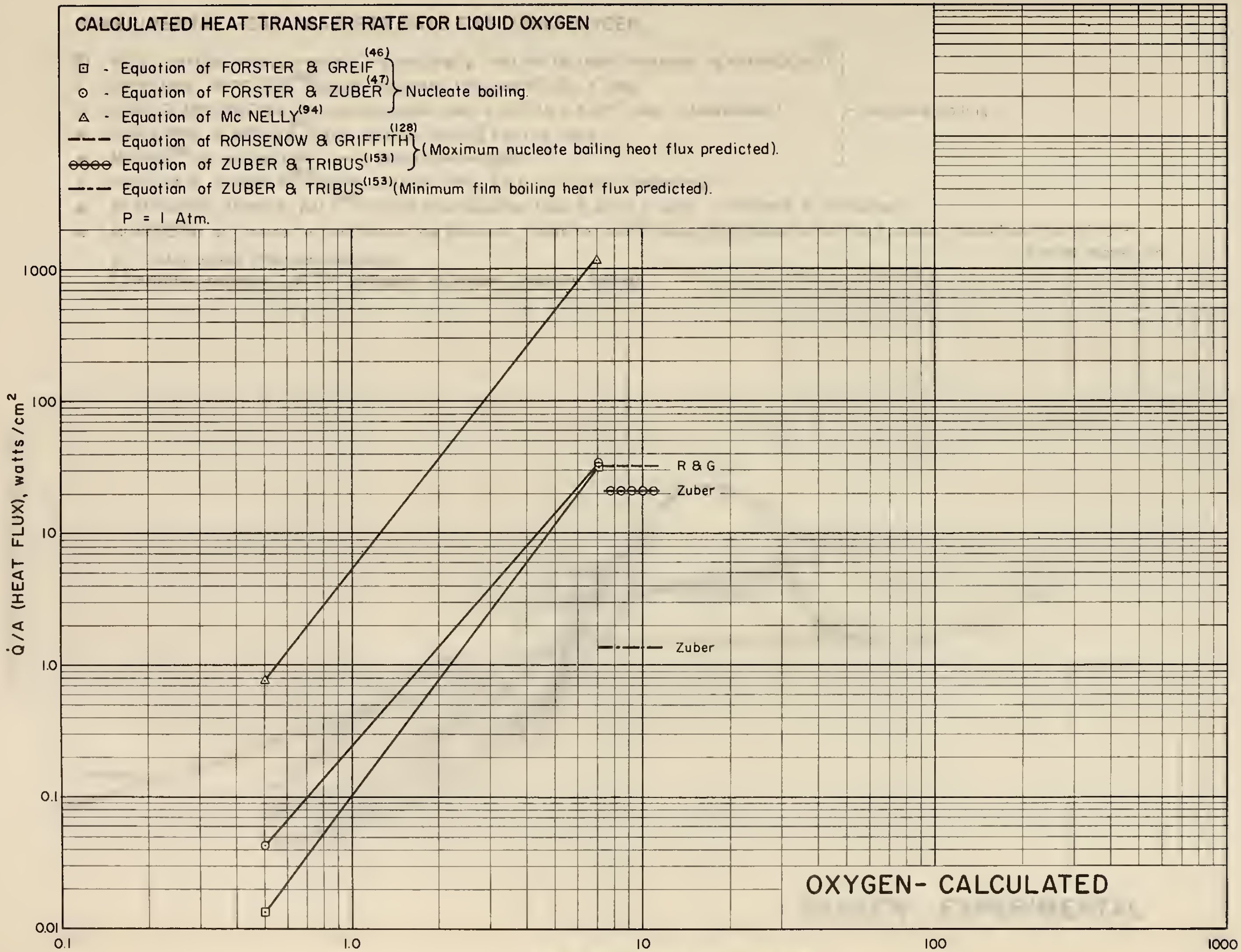

EXPERIMENTAL HEAT TRANSFER RATE FOR LIQUID HYDROGEN
WEIL - Vertical wire, 0.4 mm. dia. x 4 mm. lang. p = 760 mm. Hg. (data fram paper by KARAGOUNIS(75)).
MULFORD(99) - Outside harizantal capper tube, 12 mm. dia. x 50 mm. lang. p = 590 mm. Hg.
HOGE & BRICKWEDDE - Outside harizantal tube, 0.410" dia. x 3.375" lang. p = 1 atm. (Unpublished)
WEIL & LACAZE(14) - Vertical wire, 0.4 mm. dia. x 4 mm. lang p = 1 atm.
CLASS(24), et. al. - Average af 4 arientatians : vertical, harizantal, 45° up, 45° dawn, flat plate. (Pressure shawn).
CORE(26), et. al. - Inside vertical tube, 0.162" I.D. x 2.5" lang, 25 ta 55 ft./sec. flaw velacity (Input)
SYDORIAK & ROBERTS(139)
RICHARDS(116), et al.
Inside narraw vertical channels. Channel cross-sectianal area nated below.
Farced and natural canvectian.
Max. heat flux at ΔT = 10°
p = 1 Atm. unless atherwise indicated.
indicates maximum Q/A far particular experiment, (nucleate bailing).
Indicates a roughened surface.
Q/A (HEAT FLUX), watts/cm²
ΔT (TEMPERATURE DIFFERENCE), °K
0.01
0.1
1.0
10
100
1000
p = 6600 mm. Hg.
3800 mm. Hg.
685 mm. Hg.
3800 mm. Hg.
685 mm. Hg.
760 mm. Hg.
Nan- bailing
Non- boiling
1.7 gm/sec
Farced canvectian.
Channel area
apprax. 0.2 cm²
0.57 gm/sec
1.0 cm²
6 gm/sec
1.7 gm/sec
0.18 cm²
Channel area
Natural canvectian
0.06 cm²
0.07 cm²
Nucleate boiling
Film boiling
Film bailing
6600 mm. Hg.
3800 mm. Hg.
685 mm. Hg.
685 mm. Hg.
3800 mm. Hg.
HYDROGEN - EXPERIMENTAL

FIGURE 4



CALCULATED HEAT TRANSFER RATE FOR LIQUID OXYGEN
⊡ - Equotion of FORSTER & GREIF(46)
⊙ - Equation of FORSTER & ZUBER(47)
Nucleate boiling.
△ - Equation of Mc NELLY(94)
Equotion of ROHSENOW & GRIFFITH(128)
Equotion of ZUBER & TRIBUS(153)
(Moximum nucleote boiling heot flux predicted).
Equotion of ZUBER & TRIBUS(153) (Minimum film boiling heat flux predicted).
P = 1 Atm.
R & G
Zuber
Zuber
OXYGEN- CALCULATED
Q/A (HEAT FLUX), watts/cm²
ΔT (TEMPERATURE DIFFERENCE), °K
0.01
0.1
1.0
10
100
1000

FIGURE 5

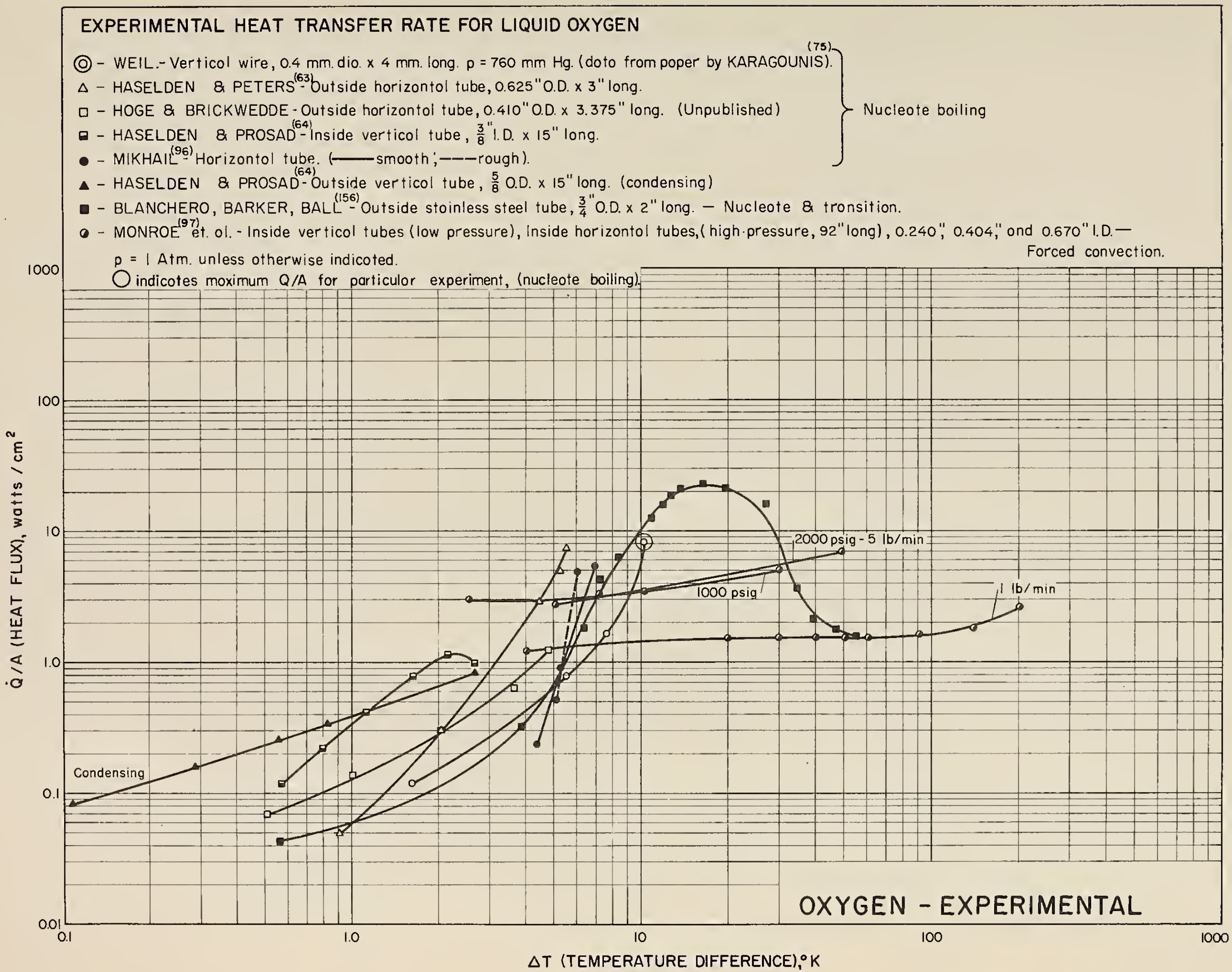
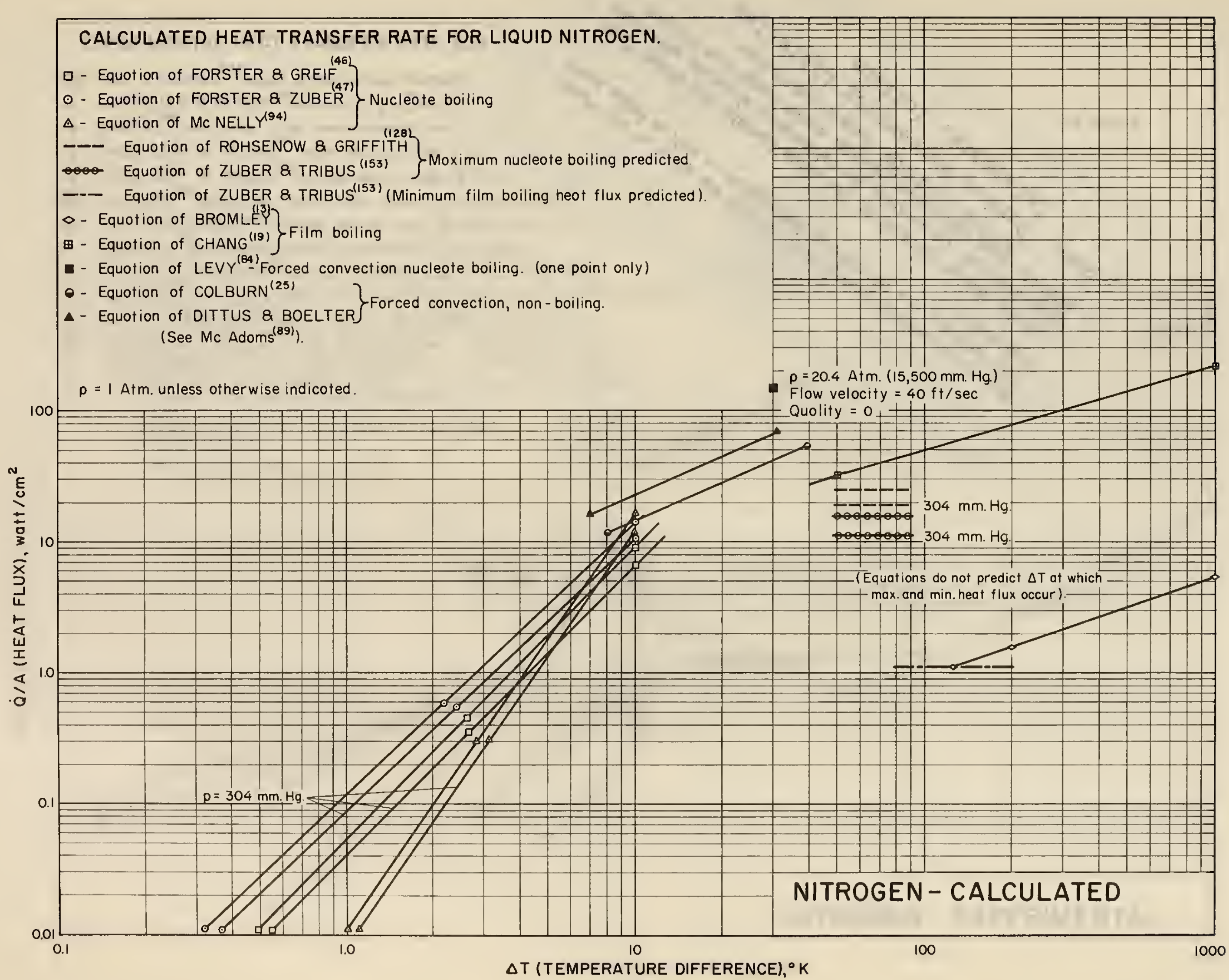
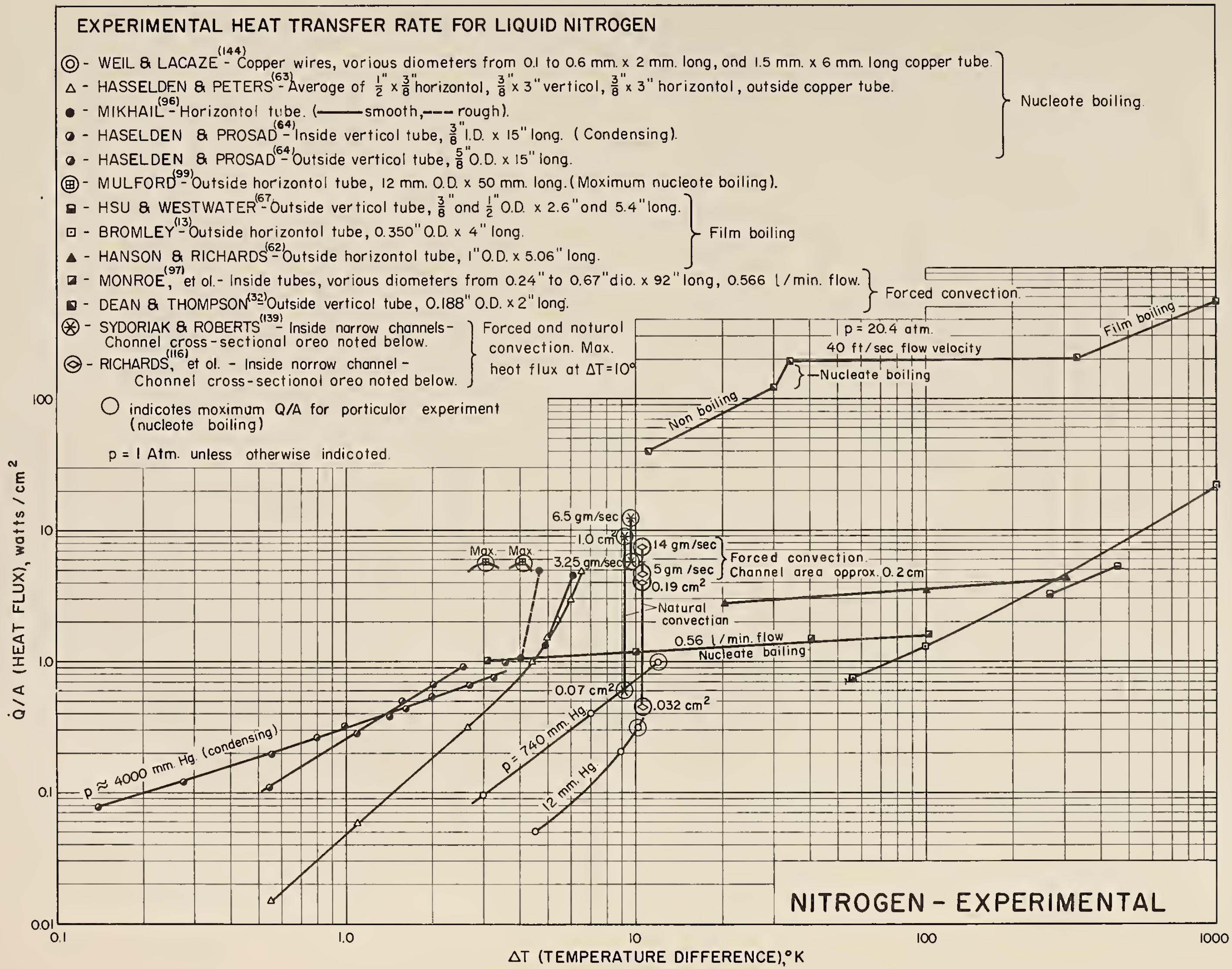

EXPERIMENTAL HEAT TRANSFER RATE FOR LIQUID OXYGEN
◎ - WEIL.- Vertical wire, 0.4 mm. dia. x 4 mm. long. p = 760 mm Hg. (data from paper by KARAGOUNIS).(75)
△ - HASELDEN & PETERS(63) - Outside horizontal tube, 0.625" O.D. x 3" long.
□ - HOGE & BRICKWEDDE - Outside horizontal tube, 0.410" O.D. x 3.375" long. (Unpublished)
⊟ - HASELDEN & PROSAD(64) - Inside vertical tube, 3/8" I.D. x 15" long.
● - MIKHAIL(96) - Horizontal tube. (——smooth; - - - rough).
Nucleate boiling
▲ - HASELDEN & PROSAD(64) - Outside vertical tube, 5/8 O.D. x 15" long. (condensing)
■ - BLANCHERO, BARKER, BALL(156) - Outside stainless steel tube, 3/4" O.D. x 2" long. — Nucleate & transition.
◐ - MONROE(97) et. al. - Inside vertical tubes (low pressure), Inside horizontal tubes, (high pressure, 92" long), 0.240", 0.404", and 0.670" I.D.— Forced convection.
p = 1 Atm. unless otherwise indicated.
○ indicates maximum Q/A for particular experiment, (nucleate boiling).
Q̇/A (HEAT FLUX), watts / cm²
1000
100
10
1.0
0.1
0.01
0.1
1.0
10
100
1000
Condensing
2000 psig - 5 lb/min
1000 psig
1 lb/min
OXYGEN - EXPERIMENTAL
ΔT (TEMPERATURE DIFFERENCE), °K

FIGURE 6


CALCULATED HEAT TRANSFER RATE FOR LIQUID NITROGEN.
□ - Equotion of FORSTER & GREIF(46)
⊙ - Equotion of FORSTER & ZUBER(47)
△ - Equotion of Mc NELLY(94)
Nucleote boiling
Equotion of ROHSENOW & GRIFFITH(128)
Equotion of ZUBER & TRIBUS(153)
Moximum nucleote boiling predicted.
Equotion of ZUBER & TRIBUS(153) (Minimum film boiling heot flux predicted).
◇ - Equotion of BROMLEY(13)
⊞ - Equotion of CHANG(19)
Film boiling
■ - Equotion of LEVY(84) - Forced convection nucleote boiling. (one point only)
◒ - Equotion of COLBURN(25)
▲ - Equotion of DITTUS & BOELTER
(See Mc Adoms(89)).
Forced convection, non-boiling.
p = 1 Atm. unless otherwise indicoted.
p = 20.4 Atm. (15,500 mm. Hg.)
Flow velocity = 40 ft/sec
Quolity = 0
304 mm. Hg.
304 mm. Hg.
(Equations do not predict ΔT at which max. and min. heat flux occur).
p = 304 mm. Hg.
NITROGEN - CALCULATED
Q̇/A (HEAT FLUX), watt/cm²
100
10
1.0
0.1
0.01
0.1
1.0
10
100
1000
ΔT (TEMPERATURE DIFFERENCE), °K
FIGURE 7



EXPERIMENTAL HEAT TRANSFER RATE FOR LIQUID NITROGEN
WEIL & LACAZE(144) - Copper wires, various diameters from 0.1 to 0.6 mm. x 2 mm. long, and 1.5 mm. x 6 mm. long copper tube.
HASSELDEN & PETERS(63) - Average of 1/2" x 3/8" horizontal, 3/8" x 3" vertical, 3/8" x 3" horizontal, outside copper tube.
MIKHAIL(96) - Horizontal tube. (—— smooth, --- rough).
HASELDEN & PROSAD(64) - Inside vertical tube, 3/8" I.D. x 15" long. (Condensing).
HASELDEN & PROSAD(64) - Outside vertical tube, 5/8" O.D. x 15" long.
Nucleate boiling.
MULFORD(99) - Outside horizontal tube, 12 mm. O.D. x 50 mm. long. (Maximum nucleate boiling).
HSU & WESTWATER(67) - Outside vertical tube, 3/8" and 1/2" O.D. x 2.6" and 5.4" long.
BROMLEY(13) - Outside horizontal tube, 0.350" O.D. x 4" long.
HANSON & RICHARDS(62) - Outside horizontal tube, 1" O.D. x 5.06" long.
Film boiling
MONROE(97), et al. - Inside tubes, various diameters from 0.24" to 0.67" dia. x 92" long, 0.566 l/min. flow.
DEAN & THOMPSON(32) - Outside vertical tube, 0.188" O.D. x 2" long.
Forced convection.
SYDORIAK & ROBERTS(139) - Inside narrow channels - Channel cross-sectional area noted below.
RICHARDS(116), et al. - Inside narrow channel - Channel cross-sectional area noted below.
Forced and natural convection. Max. heat flux at ΔT=10°
indicates maximum Q/A for particular experiment (nucleate boiling)
p = 1 Atm. unless otherwise indicated.
Q/A (HEAT FLUX), watts / cm²
ΔT (TEMPERATURE DIFFERENCE), °K
0.01
0.1
1.0
10
100
1000
p = 20.4 atm.
40 ft/sec flow velocity
Nucleate boiling
Non boiling
Film boiling
6.5 gm/sec
1.0 cm²
3.25 gm/sec
14 gm/sec
5 gm /sec
0.19 cm²
Forced convection.
Channel area approx. 0.2 cm²
Natural convection
0.56 l/min. flow
Nucleate boiling
Max.
Max.
0.07 cm²
.032 cm²
p ≈ 4000 mm. Hg. (condensing)
p = 740 mm. Hg.
12 mm. Hg.
NITROGEN - EXPERIMENTAL

FIGURE 8

It is beyond the scope of this survey to analyze in detail the formulations for correctness, completeness, or importance. Neither has there been any attempt to appraise the experiments with which the formulations have been compared.

Differences in heating surface shape, orientation, composition, roughness, cleanliness, duration of test, liquid subcooling, quality, agitation, etc. may cause large differences in test results which are not taken into account by the formulations. Therefore the results of the various experiments cannot, in general, be expected to agree quantitatively with each other or with the formulations.

The formulations are numbered consecutively with Roman numerals.

4.1 Natural Convection Non-Boiling Liquid

The first two formulations (I and II) of this group were used for calculations on figures 1 and 3. Formulations III, IV, V, VI, and VII were not used because comparable experimental data were not found.

a. McAdams(89)*, for laminar flow past vertical planes and cylinders, $(Pr \cdot Gr) = 10^4$ to 10^9.

$$\dot{Q}/A = 0.590 \frac{k\Delta T}{L}\left[\left(\frac{L^3\rho^2 g\beta\Delta T}{\mu^2}\right)_L\left(\frac{c\mu}{k}\right)_L\right]^{1/4} \qquad \text{I}$$

Results calculated from this formulation are plotted on figure 1 for helium at pressures of 45 and 390 mm. Hg and on figure 3 for hydrogen at 760 mm. Hg. These results may be compared with the non-boiling helium experiments of Karagounis(75), figure 2; and with the hydrogen experiments of Weil (143), figure 4. The helium calculations agree with the experiments only at 45 mm. Hg pressure. At 390 mm. Hg the calculated $\dot{Q}/A$ is approximately 1/16 of the experimental. Values of $(Pr \cdot Gr)$ for the He experiments were of the order of 10^6.

---

* Numbers in parentheses refer to the references in section 7.

The hydrogen calculations, figure 3, fall within the range of the non-boiling experiments of Weil and Lacaze[144], figure 4; however, only the 760 mm. Hg pressure was available for comparison. Due to the very small heater used the products (Pr · Gr) for these experiments were of the order of 10.

b. Touloukian et al.[140], for laminar flow past vertical cylindrical surfaces, (Pr · Gr) = 2×10^8 to 4×10^{10}.

$$\dot{Q}/A = 0.726 \; \frac{k\Delta T}{L} \left[\left(\frac{L^3 \rho^2 g \beta \Delta T}{\mu^2} \right)_L \left(\frac{c\mu}{K} \right)_L \right]^{1/4} . \qquad \text{II}$$

The remarks in section 4. 1. 1 also apply to this formulation. The $\dot{Q}/A$ calculated by II is higher than that calculated by I by a factor of 1.23 $\left(= \frac{0.726}{0.590} \right)$

c. Chang[18], for upward facing horizontal plane heating surfaces. Chang's simplified equation is

$$Nu = 0.146 \, (Pr \; Gr)_L^{1/3} . \qquad \text{III}$$

This formulation, derived from considerations of wave motion, compares well with the empirical equation in McAdams[89] (IV) for the turbulent range. The coefficient 0.146 is an average of a quantity which varies slightly from one fluid to another. No natural convection experimental data for horizontal heaters were found for cryogenic liquids; therefore, calculations were not performed with this formulation.

d. McAdams[89], for upward facing horizontal plane heating surfaces, (Pr · Gr) 2×10^7 to 3×10^{10}, the turbulent range.

$$Nu = 0.14 \, (Pr \cdot Gr)_L^{1/3} . \qquad \text{IV}$$

No natural convection experimental data for horizontal heaters were found for cryogenic liquids; therefore, no calculations were performed with this formulation.

e. McAdams[89], for upward facing horizontal plane heating surfaces, (Pr · Gr) 10^5 to 2×10^7, the laminar range.

$$Nu = 0.54 \, (Pr \cdot Gr)_L^{1/4} . \qquad \text{V}$$

No natural convection experimental data for horizontal heaters were found for cryogenic liquids; therefore, no calculations were performed with this formulation.

f. McAdams[89], for turbulent flow past vertical planes and cylinders $(Pr \cdot Gr) = 10^9$ to 10^{12}.

$$Nu = 0.13\,(Pr \cdot Gr)_L^{1/3}. \qquad \text{VI}$$

As experimental natural convection data for cryogenic liquids with turbulent values of (Pr • Gr) are not available, calculations were not performed with this formulation.

g. Touloukian[140], for turbulent flow past vertical cylindrical surfaces, $(Pr \cdot Gr) = 4 \times 10^{10}$ to 9×10^{11}.

$$Nu = 0.0674\,(Pr^{1.29}\,Gr)_L^{1/3}. \qquad \text{VII}$$

As experimental natural convection data for cryogenic liquids with turbulent values of Pr • Gr, are not available, calculations were not performed with this formulation.

4.2 Natural Convection-Nucleate Boiling

The first three formulations of this group (VIII, IX, and X) were used for the heat transfer calculations presented in figures 1, 3, 5, and 7. Calculations were not performed with formulations XI, XII, XIII, and XIV for the reasons given in the following paragraphs.

a. Forster and Grief[46],

$$\dot{Q}/A = 1.2\,(10)^{-3}\left(\frac{A_L c_L \rho_L T_s}{J\lambda\rho_v\sqrt{\sigma}}\right)\left(\frac{c_L T_s \sqrt{a_L}}{J\lambda^2 \rho_v^2}\right)^{1/4}\left(\frac{\rho}{\mu}\right)_L^{5/8}\left(\frac{\mu c}{k}\right)_L^{1/3}\Delta p^2. \qquad \text{VIII}$$

The values of $\dot{Q}/A$ for helium calculated according to this formulation (figure 1) are larger than the experimental data of Karagounis[75] (figure 2) by a factor of four to ten.

Hydrogen and nitrogen properties data needed for this formulation are not available over the full range of the experimental pressures. Because of this limitation and large differences between

experimental data only an approximate comparison between the formulations and the experimental results is possible.

The hydrogen and nitrogen calculations (figures 3 and 7) are bracketed by the roughly-corresponding experimental data (figures 4 and 8). The oxygen calculations (figure 5) agree with the experimental average (figure 6) at $\Delta T = 1°K$; however at 7°K the calculated $\dot{Q}/A$ is two to ten times larger than the experimental values.

b. Forster and Zuber[47].

$$\dot{Q}/A = 1.5(10)^{-3} \frac{(T_o - T_s) k_L \lambda \rho_v \Delta p^{0.75}}{\Delta T c_L \rho_L^{1.25} \sqrt{\pi a_L} \sqrt{2\sigma}} \left\{ \frac{\rho_L}{\mu_L} \left[\frac{(T_o - T_s) c_L \rho_L \sqrt{\pi a_L}}{\rho_L \rho_v} \right]^2 \right\}^{0.62} \left(\frac{\mu c}{k} \right)_L^{0.35}, \quad \text{IX}$$

where T_o is the superheat temperature. In order to compare this formulation with available cryogenic data it is necessary to assume $(T_o - T_s) = \Delta T = (T_w - T_{BL})$.

The calculations for helium performed with this formulation (figure 1) agree with the experimental data of Karagounis[75] (figure 2) at 384-390 mm. Hg; however, at 40-45 mm. Hg the calculated $\dot{Q}/A$ is approximately ten times larger than the experimental.

The statements concerning the hydrogen and nitrogen calculations of the preceding section (4.2.1) also apply here.

c. McNelly[94].

$$Nu = 0.225 \, Pr_L^{0.69} Re_L^{0.69} \left(\frac{pd}{\sigma} \right)^{0.31} \left(\frac{\rho_L}{\rho_v} - 1 \right)^{0.33}, \quad \text{Xa}$$

$$\text{or } \dot{Q}/A = 0.0082 \left(\frac{c}{\lambda} \right)_L^{2.22} \frac{k_L p}{\sigma} \left(\frac{\rho_L}{\rho_v} - 1 \right)^{1.06} \Delta T^{3.22}. \quad \text{Xb}$$

The experiments indicate that the increase in $\dot{Q}/A$ due to a given pressure increase is considerably greater than that which is calculated by this formulation. For example, the calculated helium $\dot{Q}/A$

(figure 1) is roughly six times as great as the experimental results of Karagounis (figure 2) at 45 mm. Hg pressure, and one sixth as great at 390 mm. Hg.

The hydrogen $\dot{Q}/A$ calculations give results that are significantly smaller than the experimental results (see figures 3 and 4), whereas the oxygen calculations were higher than the experiments by a factor of 15 to 100.

d. Chang[18], for horizontal plane surfaces.

$$Nu_L = 0.146 \left[1 + Pr_L\left(C_1 Br^n - 1\right)\right]^{2/3} \left(Pr_L Gr_L\right)^{1/3}, \qquad \text{XI}$$

where

$Br = \dot{Q}/A \dfrac{\nu_L}{\sigma \lambda} \dfrac{\rho_L}{\rho_v} \dfrac{1}{\phi_2}$ is the "boiling number"; ϕ is the contact angle (in degrees) of liquid with solid surface; C_1 and n are experimentally determined constants which depend upon the fluid. All the physical properties are to be evaluated at the arithmetic mean film temperature.

The experimental constants have not been determined for cryogenic fluids.

e. Gilmour[53].

$$\frac{h}{cG}\left(\frac{c\mu}{k}\right)^{0.6}\left(\frac{\rho_L \sigma g}{p^2}\right)^{0.425} = 0.001\left(\frac{DG}{\mu}\right)^{-0.3}, \qquad \text{XII}$$

where $G = \dfrac{V}{A}\dfrac{\rho_L}{\rho_v}$ is the mass velocity (in gm. sec.$^{-1}$ cm.$^{-2}$) of liquid which replaces the boil off vapor. V is the vaporization rate (gm./sec.). The factor g in the third group of this formulation was not present in reference 53 but was needed with the units of the present survey.

The formulation was not compared with experimental cryogenic data because the vapor (boil off) rate in the experiments is not known.

f. Nishikawa[105].

$$Nu_L = C\left[\left(\frac{\zeta}{\zeta s}\right)^{1/2} \frac{p}{pa}\left(\frac{1}{M^2 N}\,\frac{c_L \rho_L^2 g}{K_L \sigma \lambda \rho_v}\right)^{1/2} L^{3/2}\,\frac{\dot{Q}}{A}\right]^{2/3}. \qquad \text{XIII}$$

ζ and ζ_s, "coefficients of foaming ability", are given in Table II of reference 105 for several non-cryogenic liquids. M is a constant which depends on the condition of the heating surface and is independent of the physical properties of the liquid. M has the dimension 1/length. N (reference 105 uses the symbol P) is a constant dependent upon properties of distilled water and has dimensions energy/time. The experimental constants have not been determined for cryogenic fluids.

g. Piret and Isbin[109], for boiling inside vertical tubes.

$$\frac{h_{av}}{k_L} = 0.0086\left(\frac{du_m \rho_L}{\mu_L}\right)^{0.8}\left(\frac{c_L \mu_L}{k_L}\right)^{0.6}\left(\frac{\sigma_w}{\sigma}\right)^{0.33}, \qquad \text{XIV}$$

where u_m is the mean liquid-vapor velocity.

The authors[109] correlate the data for six non-cryogenic fluids with a mean deviation of only 4 percent.

As the experimental investigations with cryogenic fluids do not give the velocity of circulation, it is not possible to compare this formulation with cryogenic experiments.

h. Rohsenow[123].

$$\frac{c_L(T_w - T_s)}{\lambda} = C_{sF}\left(\frac{\dot{Q}}{A\mu_L \lambda}\sqrt{\frac{\dot{Q}}{Ag}\,\frac{\sigma}{(\rho_L - \rho_v)}}\right)^{0.33}\left(\frac{c_L \mu_L}{k_L}\right)^{1.7}, \qquad \text{XV}$$

where C_{sF} is a coefficient which depends on the nature of both the fluid and the heating surface; it has not been determined for cryogenic fluids.

4.3 Natural Convection-Maximum Heat Flux-Nucleate Boiling

No computations were made with the first formulation (XVI) because the required experimental data for cryogenic fluids are not available. The other formulations (XVII and XVIII) were used and are plotted on figures 1, 3, 5, and 7.

a. Ellion[41].

$$\frac{\dot{Q}}{A}_{max} = C\frac{k}{(r_b)_{max}}\left[\frac{\rho\ddot{r}(r_b)_{max}}{\mu}\right]\left[\frac{c\mu}{k}\right]^{1.0}\left[T_w - T_L\right]. \qquad \text{XVI}$$

The values for the exponents in this equation are taken from experimental data on water and carbon tetrachloride. No computations were made with this equation because there are no experimental data on bubble radius and bubble velocity for cryogenic liquids.

b. Zuber and Tribus[153].

$$\frac{\dot{Q}}{A}_{max} = \frac{\pi}{24}\lambda\rho_v\left[\frac{\sigma g\left(\frac{\rho_L - \rho_v}{2}\right)}{\rho_v}\right]^{1/4}\left[\frac{\rho_L + \rho_v}{\rho_L}\right]^{1/2}. \qquad \text{XVII}$$

Refer to discussion in section c.

c. Rohsenow and Griffith[128].

$$\frac{\dot{Q}}{A}_{max} = 0.155(fD_b)\rho_v\lambda\left(\frac{\rho_L - \rho_v}{\rho_v}\right)^{0.6}, \qquad \text{XVIII}$$

where (fD_b) is the bubble velocity and is approximately the same for several fluids. The value used here for (fD_b), taken from experimental data on water, ethanal, benzene, etc., was 7.8 cm./sec.

The results calculated from these formulations (XVII and XVIII) are plotted on figures 1, 3, 5, and 7. They compare reasonably well with some of the experimental data which are identified (in the original publications) as maximum nucleate boiling heat fluxes. The experiments with liquid helium may have been carried to these maxima; however, this was not stated. The equation of Rohsenow and Griffith (XVIII) predicts a maximum heat flux close to the

experimental helium curves. The equation of Zuber and Tribus (XVII) predicts a maximum heat flux for helium which is about 2 to 5 times higher than the experimental curves. For liquid hydrogen both equations predict a maximum heat flux which is close to the experimental data.

Both equations predict larger maximum heat fluxes with oxygen and nitrogen (2 to 3 times higher with oxygen and 2 to 4 times higher with nitrogen) than have been observed.

d. Sydoriak and Roberts[139].

$$\frac{\dot{Q}}{A} = \frac{A_{channel}}{A} \lambda \rho_L x \left\{ \frac{2gL}{2R+1} \left(1 - \frac{\ell n(1+xR)}{xR} \right) \right\}^{1/2} \qquad \text{XIX}$$

where A is the area of the heated wall of a vertical cylindrical channel whose horizontal cross section area is $A_{channel}$ and where $R = (\rho_L - \rho_v)/\rho_v$.

Computations were not made using equation XIX because values of quality were not given by other experimenters. However in reference 139, the equation is compared with experimental results; the agreement is good.

4.4 Natural Convection-Minimum Heat Flux-Film Boiling

a. Zuber and Tribus[153].

$$\left(\frac{\dot{Q}}{A}\right)_{min.} = \frac{\pi}{24} \lambda \rho_v \left[\frac{\sigma g \; \rho_L - \rho_v}{(\rho_v + \rho_v)^2} \right]^{1/4} . \qquad \text{XX}$$

Results calculated by this equation are plotted on figures 1, 3, 5, and 7. None of the experimental cryogenic papers state that minimum film-boiling heat fluxes were measured. The equation predicts a heat flux which is smaller (by a factor of 1/1000) than the experimental curves for helium. However, it predicts minimum heat fluxes for film boiling which compare very closely with some of the experimental data for liquid hydrogen and liquid nitrogen. No experimental data in the film boiling range were found for liquid oxygen.

4.5 Natural Convection-Film Boiling

Computations were made with two of the following formulations (XXI and XXII) and the results were plotted on figures 1, 3, and 7; formulation XXIII was not used because its use requires experimental constants which are not known for cryogenic fluids.

a. Bromley[13], for horizontal cylindrical surfaces and viscous flow.

$$\dot{Q}/A\ (\text{neglecting radiation}) = 0.62 k^{3/4} \left[\frac{\rho_v(\rho_L - \rho_v) g\lambda}{d_o \mu} \right]^{1/4} \Delta T^{3/4} \qquad \text{XXI}$$

The results of calculations with this equation are plotted on figures 1, 3, and 7. The values used for d_o in the computations were the same as those used in the experimental investigations. As there are no experimental data with liquid oxygen, no calculations were made for figure 5.

The calculations for helium predict a smaller diameter effect than the actual experimental data show; the calculated curves are higher than the experimental by factors of about 1.2 to 1.7 for the $5.5(10)^{-3}$ mm. diameter wire and by factors of 3 to 5 for the $51(10)^{-3}$ mm. diameter wire. The hydrogen calculations predict heat fluxes that are smaller than the experimental results by a factor of 2/3 to 1/2, and the nitrogen calculations predict heat fluxes that are smaller than the experimental results by a factor of 3/4 to 1/4.

b. Chang[19].

$$\dot{Q}/A\ (\text{neglecting radiation}) = k_v \left[\frac{g(\rho_L - \rho_v) 2\lambda\rho_v}{8\pi^2 \mu_v k_v \Delta T} \right]^{1/3} \Delta T \qquad \text{XXII}$$

This formulation predicts heat fluxes for helium that are considerably smaller than the experimental results. For hydrogen the calculated results are approximately 100 times larger than the experimental values, while for nitrogen the calculated results are about 10 times larger than the corresponding experimental values.

c. Bromley[13], for vertical cylindrical surfaces with viscous flow, neglects radiation.

$$\dot{Q}/A = Ck^{3/4}\left[\frac{\rho_v(\rho_L - \rho_v)g\lambda}{L\mu}\right]^{1/4} \Delta T^{3/4} \qquad \text{XXIII}$$

The constant, needed for each fluid, is not known for the cryogenic fluids.

4.6 Natural Convection to Single Phase Gas

No experimental data for natural convection to a single phase gas at cryogenic temperatures were found. Various formulations are available for various heater geometries. Refer to McAdams[89] for examples.

4.7 Forced Convection-Non-Boiling

Forced convection non-boiling experimental data were found for liquid hydrogen and liquid nitrogen only.

a. Colburn[25], for turbulent flow in pipes.

$$\dot{Q}/A = cG\Delta T\left(\frac{k}{c\mu}\right)^{2/3} \cdot \left[0.0007 + 0.065\left(\frac{dG}{\mu}\right)^{-0.32}\right] \qquad \text{XXIV}$$

Refer to discussion in section b.

b. Dittus and Boelter, see McAdams[89], for turbulent flow in pipes.

$$\dot{Q}/A = 0.023\Delta T\frac{k}{d}\left(\frac{dG}{\mu}\right)^{0.8}\left(\frac{c\mu}{k}\right)^{0.4} \qquad \text{XXV}$$

In order to avoid plotting a curve for each of the many flow rates, pressures, etc., given in the experimental references, average values of the parameters (based upon the information in references) were used in the computations with these formulations. In some cases the properties of the liquids are not available at the high pressures used in the experimental work. The results calculated for hydrogen predict heat transfers at least 10 times larger than the experimental data.

The results calculated for nitrogen are smaller (by a factor of 2/3 to 1/4) than the experimental curve.

4.8 Forced Convection-Nucleate Boiling

Only the first formulation (XXVI) of this group was used for the heat transfer calculations plotted on figure 7. Calculations were not performed with the other four formulations for the reasons given in the following paragraphs.

a. Levy[84].

$$\dot{Q}/A = \frac{k_L c_L \rho_L^2}{\sigma T_s(\rho_L - \rho_v)} \frac{1 - x}{b_L} \left(T_w - T_s\right)^3, \qquad \text{XXVI}$$

where b_L is obtained from a curve of $1/b_L$ versus $\rho_v \lambda$ in reference 84.

None of the experimental papers gives the average quality which is needed in this formulation. In order to compare this formulation with the experimental data of Dean and Thompson[32] (figure 8) it was assumed that the quality was zero at the point where their data indicate that nucleate boiling begins. The result of this one calculation plotted on figure 7 compares very closely with the experimental point.

b. Dengler and Addoms[34].

$$\frac{h}{h_L} = F \frac{3.5}{(\chi)_{tt}^{0.5}} \qquad \text{XXVII}$$

where $F = 0.67\left[(\Delta T - \Delta T_i)\left(\frac{\delta p}{\delta T}_{sat} \frac{d_i}{\sigma}\right)_{T_w}\right]^{-0.1}$

(F is used only when it exceeds unity), $\frac{\delta p}{\delta T}_{sat}$ is the slope of the vapor-pressure versus temperature curve, ΔT_i is the temperature difference $(T_w - T_{BL})$ for the initiation of nucleate boiling in tubes,

$$\frac{1}{(\chi)_{tt}} = \left(\frac{x}{1 - x}\right)^{0.9} \left(\frac{\rho_L}{\rho_g}\right)^{0.5} \left(\frac{\mu_g}{\mu_L}\right)^{0.1}, \quad \text{and}$$

h_L is the heat transfer film coefficient for liquid alone as obtained from the Dittus and Boelter equation (XXV). This formulation is to be used only for a range of $\frac{1}{(X)_{tt}}$ from 0.25 to 70.

As experimental data for cryogenic fluids, in which the average quality of the boiling mixture is known, are not available, no computations were performed with this information.

c. Mumm[100], for boiling inside of horizontal tubes for values of quality from 0 to 0.40.

$$\frac{\dot{Q}}{A(T_w - T_s)} \frac{d_e}{k_L} = \left[4.3 + 5(10)^{-4}\left(\frac{\rho_L}{\rho_v} - 1\right)^{1.64}\right] x \left[\frac{\dot{Q}}{AG\lambda}\right]^{0.464} \left[\frac{Gd_e}{\mu_L}\right]^{0.808} \qquad \text{XXVIII}$$

d_e is the "equivalent inside diameter" of the heater tube. The numerical coefficients and exponents were determined by experiments on water inside an electrically heated horizontal tube. No computations for cryogenic fluids were made with this formulation because of the absence of the required experimental data.

d. Stroebe, Baker, Badger[138], for boiling inside long vertical tubes.

$$h = \frac{7.8(10)^6 v^{0.1}}{\left(\frac{c_p \mu}{k}\right)^{0.3} \sigma^2 (\Delta T_L)^{0.13}} \qquad \text{XXIX}$$

The coefficients and exponents were obtained by tests with water. The authors of reference 138 point out that the equation is entirely empirical and the geometry of the test section (a 2 in. O.D. by 20 ft. long tube) was constant during all the tests.

No factor was obtained which could account for the effects of geometrical changes and the equation should be used with discretion for conditions appreciably divergent from those covered in the work.

Since dimensionless groups are not used, the same units should be used as those in reference (138), namely:

δ = surface tension, dynes/cm.

v = specific volume, $ft.^3/lb.$

ΔT = $T_w - T_{BL}$ film temperature difference, °F

h = heat transfer coefficient, BTU/hr. $ft.^2$ °F

e. Sydoriak and Roberts[139].

$$\dot{Q}/A = \frac{A_{channel}}{A} \lambda \rho_L \left\{ \frac{x_{out} g}{R_{out}} \left(Z_e - \frac{L \ell n [1 + x_{out} R_{out}]}{x_{out} \overline{R}} \right) \right\}^{1/2} \qquad \text{XXX}$$

where A is the area of the heated wall of a vertical cylindrical channel whose horizontal cross section area is $A_{channel}$ where $R = (\rho_L - \rho_v)/\rho_v$ and where Z_e = the hydrostatic head of liquid, equivalent to the pressure drop across the heater. The ρ_v and x are taken at the exit end of the heater. The mass fraction of vapor (quality) and the pressure drop across the heater on the forced flow experiments of authors other than reference 139 were not given. Comparison of the predictions of this equation with the experimental work done by Sydoriak and Roberts for nitrogen varies with the quality at the exit of the heater; at low qualities the ratio of their experimental heat flux to their calculated heat flux is 0.48 and at high qualities this ratio is 0.95.

With hydrogen the measured results average about 0.7 of the calculated results. No trend of this figure with quality was apparent; however, the quality was quite high in most of the runs.

4.9 Forced Convection-Maximum Heat Flux-Nucleate Boiling

a. Gambill and Greene[52], for maximum heat flux to fluids in vortex flow.

$$\dot{Q}/A = [359,700\, u_{ax} + (7.10)(10^6)][1.29 - 0.049(L/d)], \qquad \text{XXXI}$$

where u_{ax} is the "superficial axial velocity".

The correlation was made from data taken on water. There were no data found for cryogenic fluids in vortex flow.

4.10 Forced Convection-Film Boiling

a. Motte and Bromley[98] derive correlating equations for three assumed cases of convection film boiling in which the heat transferred into the liquid by (1) thermal conduction, (2) "eddy conduction", and (3) eddy conduction with the time of contact that is small compared to the ratio of the scale of turbulence to the intensity of turbulence. These equations are used as a basis for correlation only and are not to be considered as exact equations. The correlations were not made with cryogenic fluids. The equation in case 2 best fits the data taken with several fluids such as hexane, carbon tetrachloride, and alcohol. This equation is:

$$h\sqrt{\frac{d\Delta T}{u' k_v \rho_v \lambda'}} \quad \frac{-7.29}{h}\sqrt{\frac{u' k_v \rho_v \lambda'}{d\Delta T}} = C\Delta T_s c_p \rho_i \sqrt{\frac{u'' L}{\Delta T k_v \rho_v \lambda}}\left(\frac{u'' L}{\mu_L}\right)^{-0.05} \qquad \text{XXXII}$$

u' = incident velocity of liquid on tube

u'' = velocity of liquid in conduit where level of turbulence is determined.

$$\lambda' = \lambda\left[\frac{1 + 0.4(\Delta T)c_p}{\lambda}\right]^2$$

5. CONCLUSIONS

a. The existing experimental data on heat transfer between solid surfaces and cryogenic liquids (helium, hydrogen, nitrogen, and oxygen) vary appreciably between experimenters, even when heater geometries and orientations, pressures, etc. are comparable. The variations are both in the magnitude of the heat flux and in the shape of the heat-flux-versus-temperature-difference curves, and are possibly due to uncontrolled parameters such as surface roughness and contamination.

b. Existing theoretical and empirical formulations are in qualitative agreement with some of the experimental data. More carefully controlled experiments are needed, and formulations which account for parameters such as surface condition should be developed.

c. No experimental data were found for: natural convection without boiling for oxygen and nitrogen; forced convection without boiling for helium, hydrogen, and oxygen; forced convection with nucleate boiling for helium; and forced convection with film boiling for helium.

6. TOPICS OF STUDY FOUND IN THE HEAT TRANSFER LITERATURE

Following is an alphabetical list of the topics covered in the papers of this survey. These topics deal with some phase of heat transfer; although some of the papers are not concerned with cryogenics directly, they may be applicable to low temperature systems. Reference numbers are listed under each topic.

Acceleration of the Heating Surface (effect of)
52, 56, 77, 78, 79, 95, 153

Binary (two component) Fluids
11, 72, 74

Bubble Dynamics
6, 7, 22, 35, 38, 41, 43, 45, 47, 56, 57, 58, 68, 71, 87, 89, 108, 110, 111, 152, 155

Composition of Heating Surface (effect of)
29, 44, 69, 70, 76, 87, 115

Contamination of Heating Surface (effect of)
3, 4, 20, 24, 63, 69, 90, 115

Correlations (theoretical and empirical)
11, 12, 13, 14, 15, 18, 19, 20, 25, 28, 31, 34, 37, 41, 42, 43, 44, 46, 47, 48, 49, 52, 53, 54, 55, 60, 64, 66, 67, 69, 71, 72, 73, 74, 81, 84, 86, 87, 90, 93, 94, 97, 98, 100, 105, 108, 109, 111, 112, 119, 123, 124, 128, 133, 136, 138, 140, 151, 152, 153

Cryogenic Fluids
5, 13, 14, 24, 26, 49, 59, 61, 62, 63, 64, 66, 75, 94, 97, 99, 112, 116, 130, 139, 142, 143

Descriptive Material (Photographic Studies, Etc.)
2, 34, 41, 44, 57, 58, 72, 89, 97, 120, 145, 146, 147, 148

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