P.A. HILTON LTD.

EXPERIMENTAL
OPERATING
AND
MAINTENANCE MANUAL

BOILING HEAT TRANSFER UNIT

H654

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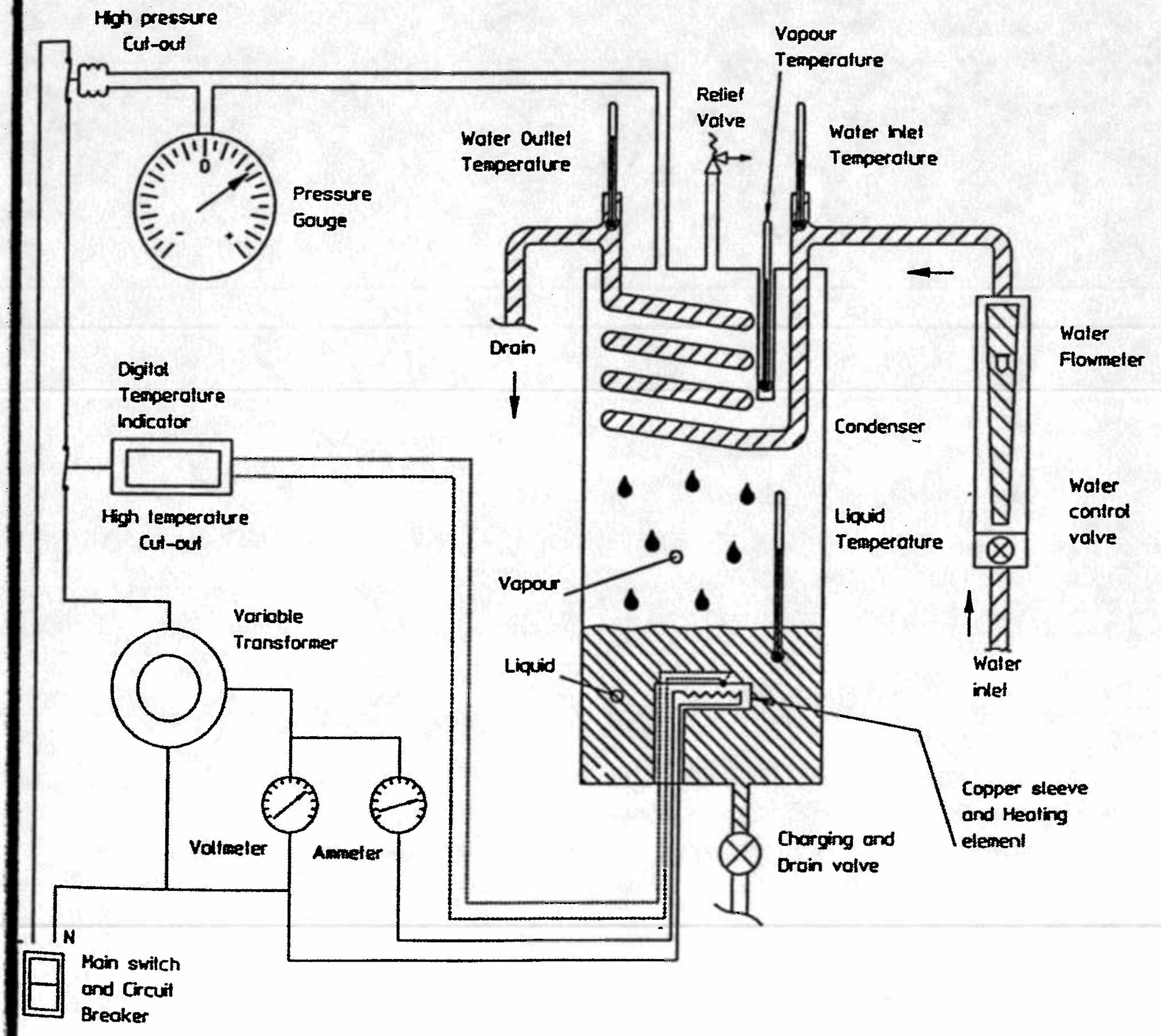
H654 Boiling Heat Transfer Unit



SYMBOLS AND UNITS

Symbol	Quantity	Fundamental Unit
A	Area	m^2
I	Current	Amps
ρ	Density	$kg\ m^{-3}$
ϕ	Heat Flux	$W\ m^{-2}$
$\dot{Q}$	Heat Transfer Rate	W
E	Potential Difference	Volts
$\dot{m}_w$	Mass Flow Rate (Water)	$kg\ s^{-1}$
l_n	Natural log	-
p	Pressure (absolute)	$N\ m^{-2}$*
C_p	Specific Heat Capacity $\frac{\Delta h}{\Delta t}$	$J\ kg^{-1}\ K^{-1}$
h	Specific Enthalpy	$J\ kg^{-1}$
h	Surface Heat Transfer Coefficient	$W\ m^{-2}\ K^{-1}$
Δt or θ	Temperature Difference	K
t	Temperature (Empirical)	°C
U	Overall Heat Transfer Coefficient	$W\ m^{-2}\ K^{-1}$

Presentation of Numerical Data

In this manual, numerical quantities obtained during experiments, etc., are expressed in a non-dimensional manner. That is, the physical quantity involved has been divided by the units in which it has been measured.

As an example:

Pressure	$\frac{p}{10^3\ Nm^{-2}}$	150	

This indicates that $$\frac{p}{10^3\ Nm^{-2}} = 150$$

or $$p = 150 \times 10^3\ N\ m^{-2}$$

alternatively $$p = 150\ kN\ m^{-2}$$

*Absolute Pressure = Gauge Pressure + Atmospheric Pressure

Suffixes

f	A property of Saturated Liquid
g	A property of Saturated Vapour
fg	A change from Saturated Liquid to Saturated Vapour
l	Liquid Temperature
m	Metal Surface Temperature
i	Inlet Temperature of Water
o	Outlet Temperature of Water
s	Saturation Temperature

USEFUL DATA

Dimensions of heating surface: Effective length = 42mm
Diameter = 12.7mm
Surface area = 0.0018m^2 (including area of end)

Condenser surface area: 0.032m^2

Maximum permitted surface temperature: 220°C

Heater cut out temperature: 160°C

Fluid: 1,1-Dichloro-1-fluoroethane (R141b) $C\,Cl_2\,F\text{-}CH_3$

Quantity of fluid: Liquid level to be not less than 50mm above heating element. Approximately 0.55 l.

Dimensions of glass chamber: Nominal internal diameter = 80mm
Length = 300mm
Volume = 0.0015m^3

Specific heat capacity of water (C_{pw}): 4.18 kJ kg^{-1} K^{-1}

1 bar = 10^5 N m^{-2} = 100 kN m^{-2}

INTRODUCTION

Boiling and condensation are vital links in the transfer of heat from a hot to a colder region in countless applications, e.g. thermal and nuclear power generation in steam plants, refrigeration, refining, heat transmission, etc.

Boiling

When a liquid at saturation temperature is in contact with the surface of a solid (usually metal) at a higher temperature, heat is transferred to the liquid and a phase change (evaporation) of some of the liquid occurs.

The nature and rate of this heat transfer changes considerably as the temperature difference between the metal surface and the liquid is increased.

Although "boiling" is a process familiar to everyone, the production of vapour bubbles is a very interesting and complex process.

Due to surface tension, the vapour inside a bubble must be at a higher pressure than the surrounding liquid. The pressure difference increases as the diameter of the bubble decreases, and is insignificant when the bubble is large.

However, when the bubble is minute, an appreciable pressure difference exists. (An analogy may be drawn with the inflation of a child's balloon - it is difficult to inflate when the balloon is small, but it becomes much easier as the diameter increases).

The pressure inside a bubble is the vapour pressure corresponding with the temperature of the surrounding liquid. Thus, when no bubbles exist (or are very small) it is possible for the liquid temperature in the region of the heat transfer surface to be well above the temperature of the bulk of the liquid. (This will be close to the saturation temperature corresponding with the pressure at the free liquid-vapour interface).

The formation of bubbles normally associated with boiling is influenced by the foregoing.

Convective Boiling

When the heating surface temperature is slightly hotter than the saturation temperature of the liquid, the excess vapour pressure is unlikely to produce bubbles. The locally warmed liquid expands and convection currents carry it to the liquid-vapour interface where evaporation takes place and thermal equilibrium is restored.

Thus, in this mode, evaporation takes place at small temperature differences and with no bubble formation.

Nucleate Boiling

As the surface becomes hotter, the excess of vapour pressure over local liquid pressure increases and eventually bubbles are formed. These occur at nucleating points on the hot surface where minute gas pockets, existing in surface defects form the nucleus for the formation of a bubble.

As soon as a bubble is formed, it expands rapidly as the warmed liquid evaporates into it. The buoyancy detaches the bubble from the surface and another starts to form.

Nucleate boiling is characterised by vigorous bubble formation and turbulence. Exceptionally high heat transfer rates and heat transfer coefficients with moderate temperature differences occur in nucleate boiling, and in practical applications, boiling is nearly always in this mode.

Film Boiling

Above a critical surface-liquid temperature difference, it is found that the surface becomes "vapour locked" and the liquid is unable to wet the surface. When this happens there is a considerable reduction in heat transfer rate and if the heat input to the metal is not immediately reduced to match the lower ability of the surface to transfer heat, the metal temperature will rise until radiation from the surface plus the limited film boiling heat transfer, is equal to the energy input.

If the energy input is in the form of work (including electrical energy) there is no limit to the temperature which could be reached by the metal and its temperature can rise until a failure or a "burn out" occurs. If the source is radiant energy from, for example, a combustion process, a similar failure can occur, and many tube failures in the radiant section of advanced boilers are attributed to this cause.

Immersion heaters must obviously be designed with sufficient area so that the heat flux never exceeds the critical value.

The consequences of a "burn out" in a nuclear power plant will be readily appreciated.

Condensing Heat Transfer

Condensation of a vapour onto a cold surface may be "filmwise" or "dropwise".

When filmwise condensation occurs, the surface is completely wetted by the condensate and condensation is onto the outer layer of the liquid film, the heat passing through the film and into the surface largely by conduction.

By treating a surface with a suitable compound it may be possible to promote "dropwise" condensation. When this occurs the surface is not wetted by the liquid and the surface becomes covered with beads of liquid which coalesce to form drops which then fall away leaving the surface bare for a repetition of the action.

Heat transfer coefficients with dropwise condensation are higher than with filmwise owing to the absence of the liquid film.

For a complete investigation of filmwise and dropwise condensation at high heat fluxes, the Hilton Film and Dropwise Condensation Unit H910 should be used.

Boiling and condensating heat transfer are indispensable links in the production of power, all types of refining and chemical processes, refrigeration, heating systems, etc.

There is a constant pressure for more compact heat transfer units with high heat transfer rates and a clear understanding of the boiling and condensing processes is essential for every mechanical and chemical engineer.

The Hilton Boiling Heat Transfer Unit has been designed to improve the understanding of boiling and condensing heat transfer and enables both a visual and analytical study of these processes.

During Use

Control the saturation pressure to the desired value by:
(a) Variation of the cooling water flow rate (or temperature)
(b) Variation of the power supplied to the heater.

After Use

Always:
(a) Switch off the electrical supply and disconnect from the mains.
(b) Circulate cooling water until pressure has fallen to atmospheric or below.

(ii) DETERMINATION OF HEAT FLUX AND SURFACE HEAT TRANSFER COEFFICIENT AT CONSTANT PRESSURE

Adjust the electric heater to about 30 Watts and adjust the water flow rate until the desired pressure is reached. Note the voltage, current, vapour pressure, liquid temperature and metal temperature. Increase the power to say 70 Watts, adjust the cooling water flow rate to give the desired pressure and when steady, wait 5 minutes then repeat the observation.

Repeat in similar increments until the transition from nucleate to film boiling is reached. By careful adjustment of voltage near this condition it is possible to make an accurate assessment of critical conditions. When film boiling is established the voltage should be reduced and the readings continued until the heater temperature reaches 160°C.

Typical results and graphs 1 and 2 are shown on Pages 19 and 27-28.

100V – 30kPa
125V – 47kPa

STOP

Typical results at a pressure of 175 kN m^{-2} absolute:

Voltage	$\frac{E}{Volts}$	50	75	100	120	130	135	140	145	50	55	60
Current	$\frac{I}{Amps}$	0.68	1.01	1.36	1.64	1.78	1.85	1.91	2.00	0.68	0.74	0.81
Liquid Temperature	$\frac{t_s}{°C}$	49	49	50	49	50	50	50	50	48	49	48
Metal Temperature	$\frac{t_m}{°C}$	56	59	62	64	65	66	67	80	140	150	170

From which:

Heat Transfer Rate = EI	$\frac{Q}{W}$	34	76	136	197	213	250	267	290	34	41	49
Heat Flux = $\frac{Q}{A}$	$\frac{\phi}{kW\ m^{-2}}$	19	42	76	109	118	139	148	161	19	23	27
Temperature Difference = $t_m - t_s$	$\frac{\Delta t}{K}$	7	10	12	15	15	16	17	30	92	101	122
Surface Heat Transfer Coefficient = $\frac{\phi}{\Delta t}$	$\frac{h}{kW\ m^{-2}\ K^{-1}}$	2.7	4.2	6.3	7.3	7.9	8.7	8.7	5.4 *	0.21	0.23	0.22

Note: The effective area (A) of the heat transfer surface of the heater is 1.8 x 10^{-3} m^2

These results are most conveniently plotted on a log-log graph as shown in Graphs 1 and 2 (Pages 27 and 28).

*Transition Region

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(iii) EFFECT OF PRESSURE ON CRITICAL HEAT FLUX

The method is similar to that given under (ii) but by careful adjustment of the power and water flow rate, the heat flux at transition from nucleate to film boiling at a variety of pressures may be established.

STOP

Typical results are:

Pressure $\frac{p}{\text{kN m}^{-2}}$	60	100	125	150	175	200	225	250
Heat Input $\frac{\dot{Q}}{\text{W}}$	241	267	281	292	309	328	338	349

From which:

Critical Heat Flux Φ $\frac{\phi}{\text{kW m}^{-2}}$	134	148	156	162	172	182	188	194

These results are shown graphically in Graph 3, Page 29.

(iv) FILMWISE CONDENSATION

The filmwise condensation which occurs with R141b can be clearly seen, and the resistance offered by the liquid is readily appreciated.

The overall heat transfer coefficient between the condensing vapour and the water may be found as follows:

> Adjust the voltage and water flow rate until the desired pressure and condensing rate is established. When conditions are stable, note the water flow rate, water inlet and outlet temperatures and the saturation temperature of the R141b.

Typical Results

Water flow rate $\dot{m}_w$ = 5.5 gram s^{-1}
Water inlet temperature t_i = 20.5°C
Water outlet temperature t_o = 25.0°C
Saturation temperature of liquid t_s = 29.0°C
Voltage 95V
Current 1.3V

Heat transfer rate at cooling coil, $\dot{Q}_w = \dot{m}\,Cp(t_o - t_i)$

$$= 5.5 \times 10^{-3} \times 4180(25.0 - 20.5)\ W$$

$$= \underline{104\ W}$$

Heat transfer rate from heater, $\dot{Q}_e = EI$

$$= 95 \times 1.3\ W$$

$$= \underline{124\ W}$$

Heat transfer to surroundings (by difference), $= \dot{Q}_e - \dot{Q}_w$

$$= 124 - 104\ W$$

$$= \underline{20\ W}$$

$$\phi_1 = t_s - t_i = 29.0 - 20.5 = 8.5\ K$$

$$\phi_2 = t_s - t_o = 29.0 - 25.0 = 4.0\ K$$

Log mean temperature difference,

$$\phi_m = \frac{\phi_1 - \phi_2}{l_n \dfrac{\phi_1}{\phi_2}}$$

$$= \frac{8.5 - 4.0}{l_n \dfrac{8.5}{4.0}}\ K$$

$$= \underline{6.0\ K}$$

Overall heat transfer coefficient,

$$U = \frac{\dot{Q}_w}{\phi_m}$$

$$= \frac{104}{0.032 \times 6.0} \ W\,m^{-2}\,K^{-1}$$

$$= \underline{\underline{542}} \ W\,m^{-2}\,K^{-1}$$

This may be repeated at other water flow rates, other saturation temperatures and other condensation heat fluxes.

(v) CAUSES OF PRIMING IN BOILERS

Among the causes of "carry over" or "priming" in boilers are,

(a) Operating at a lower pressure than that for which the boiler is designed.

(b) Short term heavy demands in excess of the heat input, causing formation of flash steam.

The boiling action inside the glass cylinder is similar to that occurring in a boiler on load, and students readily appreciate the problem of liquid carry over if the following demonstration is made.

Apply about 200 W to the heater and pass a large water flow through the condenser so that the saturation temperature is low. When conditions are stable, observe the rate and degree of ebullition and turbulence. Now decrease the water flow rate so that the saturation pressure is approximately doubled and again observe the degree of ebullition. It will be seen that there is an appreciable reduction in this as the pressure is raised and the probability of carry over in a practical boiler is reduced. This is accounted for by the increase of vapour density and consequent reduction of the volume of vapour leaving the liquid.

If the cooling water flow rate is now suddenly increased, a short term heavy demand is simulated. The pressure will drop, and flash evaporation will occur, in addition to the boiling caused by the heat transfer. Violent ebullition will occur and the likelihood of carry over in a practical boiler will be appreciated.

(vi) PRESSURE-TEMPERATURE RELATIONSHIP

The relationship between the saturation pressure and temperature of a pure substance is readily demonstrated up to a maximum pressure of 220 kN m^{-2} gauge. The electrical supply is switched on and adjusted to about 100 W. Cooling water is circulated at the maximum rate and when conditions are stable the pressure and temperature are noted. The cooling water flow is reduced and the observations are repeated at a higher pressure, and so on.

Results may be compared with those on Graph 4, page 30.

If a supply of chilled water is available this may be circulated through the coil and the saturation pressure will then become less than atmospheric. This is a useful demonstration and helps to dispel the belief held by many students that a vacuum pump is necessary to produce the sub-atmospheric pressures in a steam plant.

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(vii) EFFECT OF AIR IN A CONDENSER

Air may be deliberately admitted to the chamber by either:

(a) Pulling on the relief valve spindle (provided the pressure in the cylinder is below atmospheric), or

(b) Using an air pump or syringe to inject air through the charging/drain valve.

The overall heat transfer coefficient may be determined in the same manner as under section (iv). This value can be compared with the coefficient at a similar flow rate and saturation temperature when only R141b vapour is present.

It will be found that the heat transfer rate and coefficient is appreciably less when air is present and the detrimental effect of air is readily demonstrated.

The effect of air blanketing can also be demonstrated visually. With air in the cylinder and at fairly high heat transfer rate it will be found that some of the condenser coils are quite dry. If the stem of the relief valve is lifted to release the air, vigorous condensation will be seen to take place on those coils, and the rate of condensation will show a marked increase.

(viii) DEMONSTRATION OF LAW OF PARTIAL PRESSURES

With the electrical power switched off, circulate cold (<20°C) water through the condenser and a partial vacuum will be produced. Open the charging valve allowing a measured quantity of air to enter the cylinder and then close the valve. (A measured quantity of air may be obtained by connecting a syringe to the charging valve or by connecting the charging valve to the air in an inverted measuring cylinder with its open end in water.) The volume of the space over the refrigerant liquid in the cylinder may be measured and the pressure of the admitted air calculated from the gas equation.

The total pressure of the air and R141b is indicated by the pressure gauge and this may be compared with the sum of the vapour and air pressures at a variety of temperatures.

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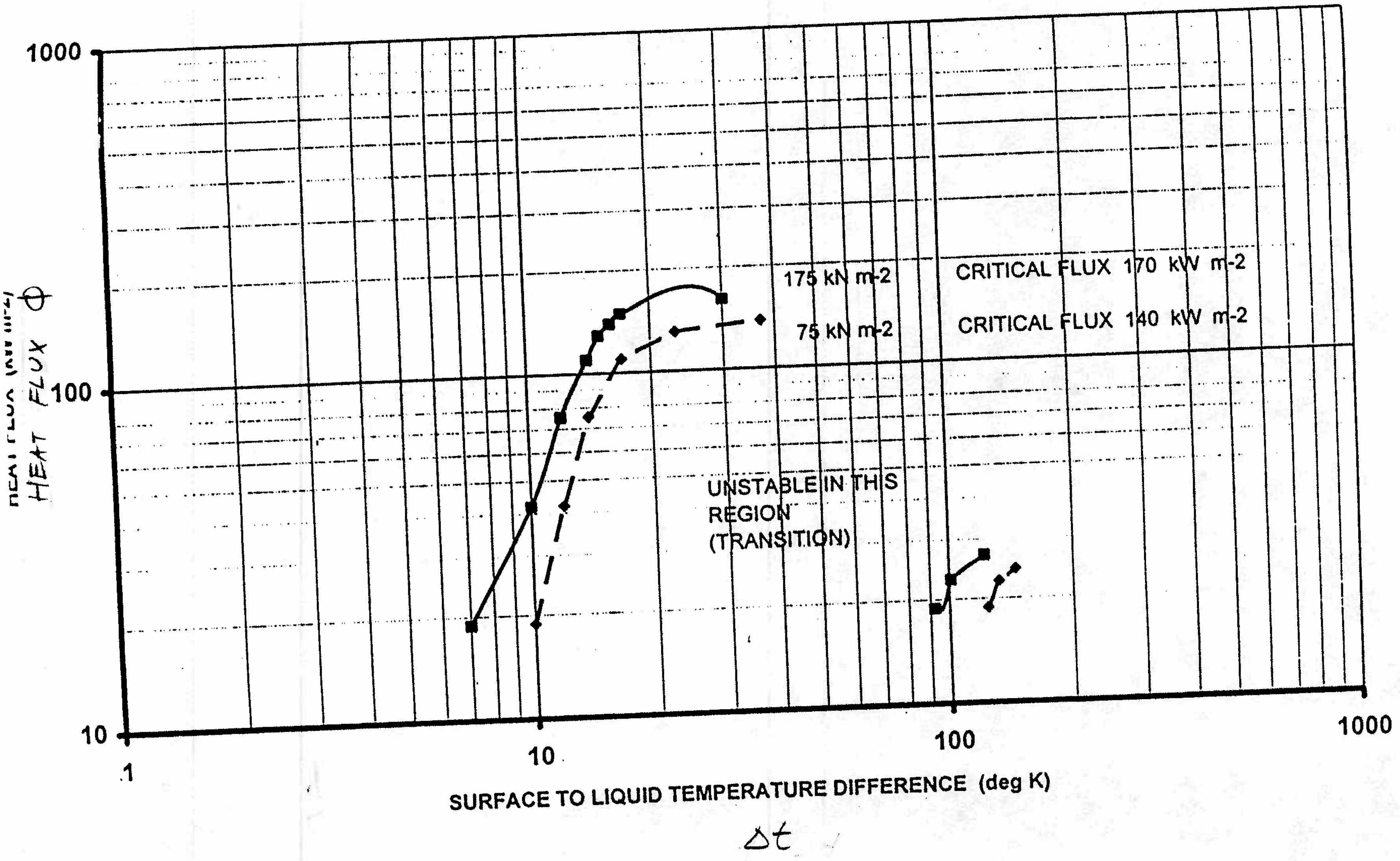
(Monday's Class)

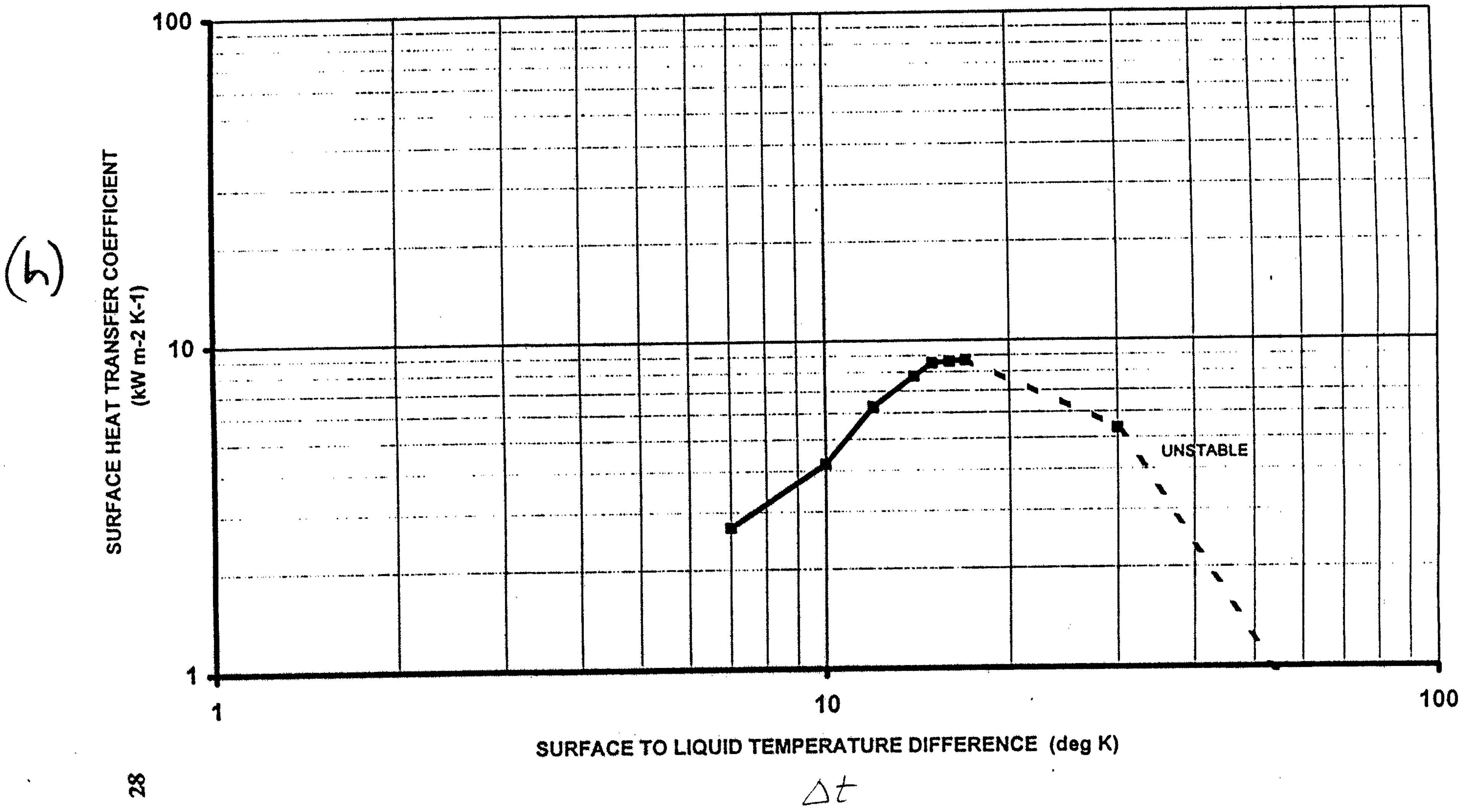
HEAT FLUX v. SURFACE TO LIQUID TEMPERATURE DIFFERENCE



GRAPH 1

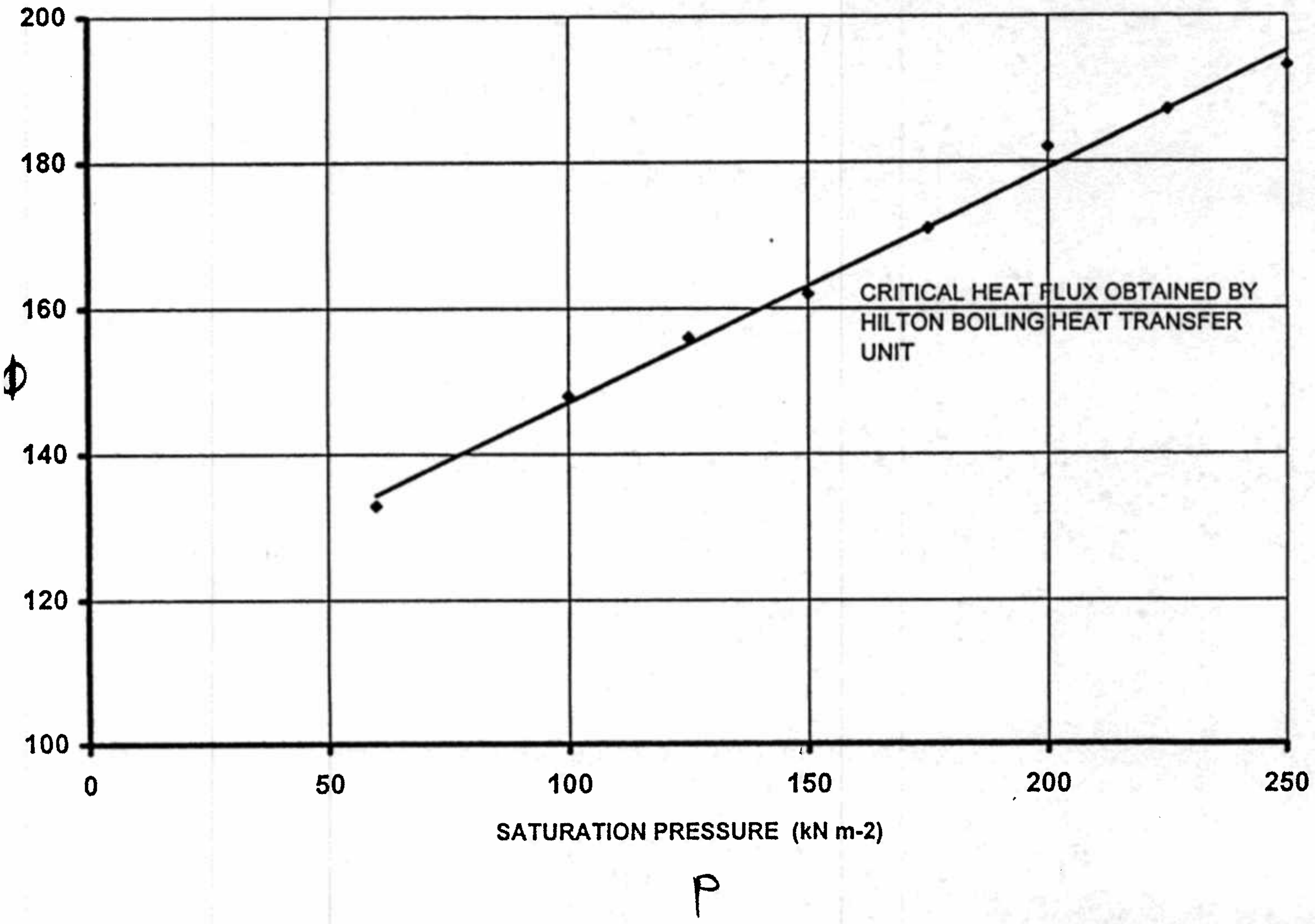
(Monday's Class)

SURFACE HEAT TRANSFER COEFFICIENT v. SURFACE TO LIQUID TEMPERATURE DIFFERENCE
Pressure = 175 kN m-2



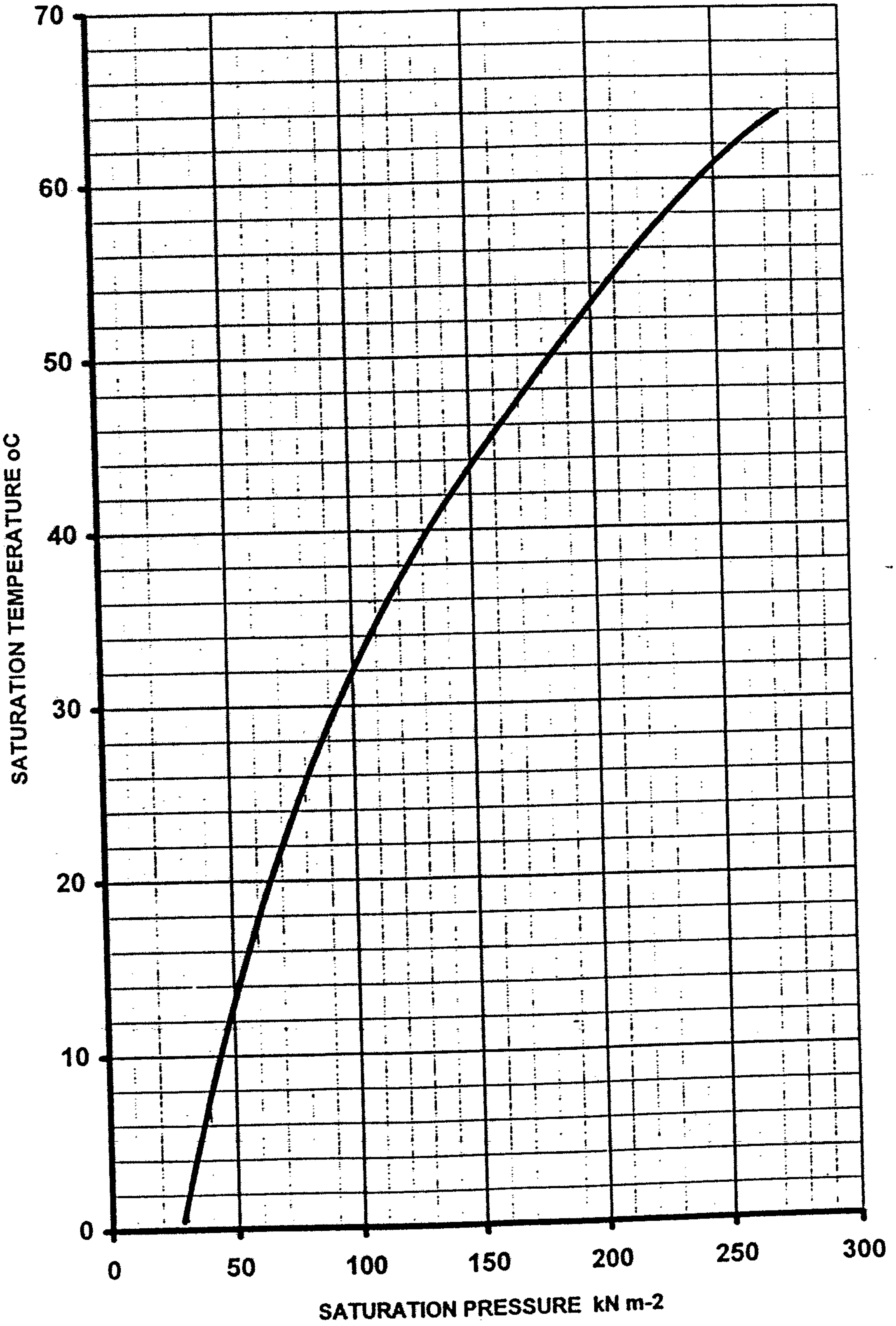
(Tuesday's Class)

CRITICAL HEAT FLUX v. SATURATION PRESSURE

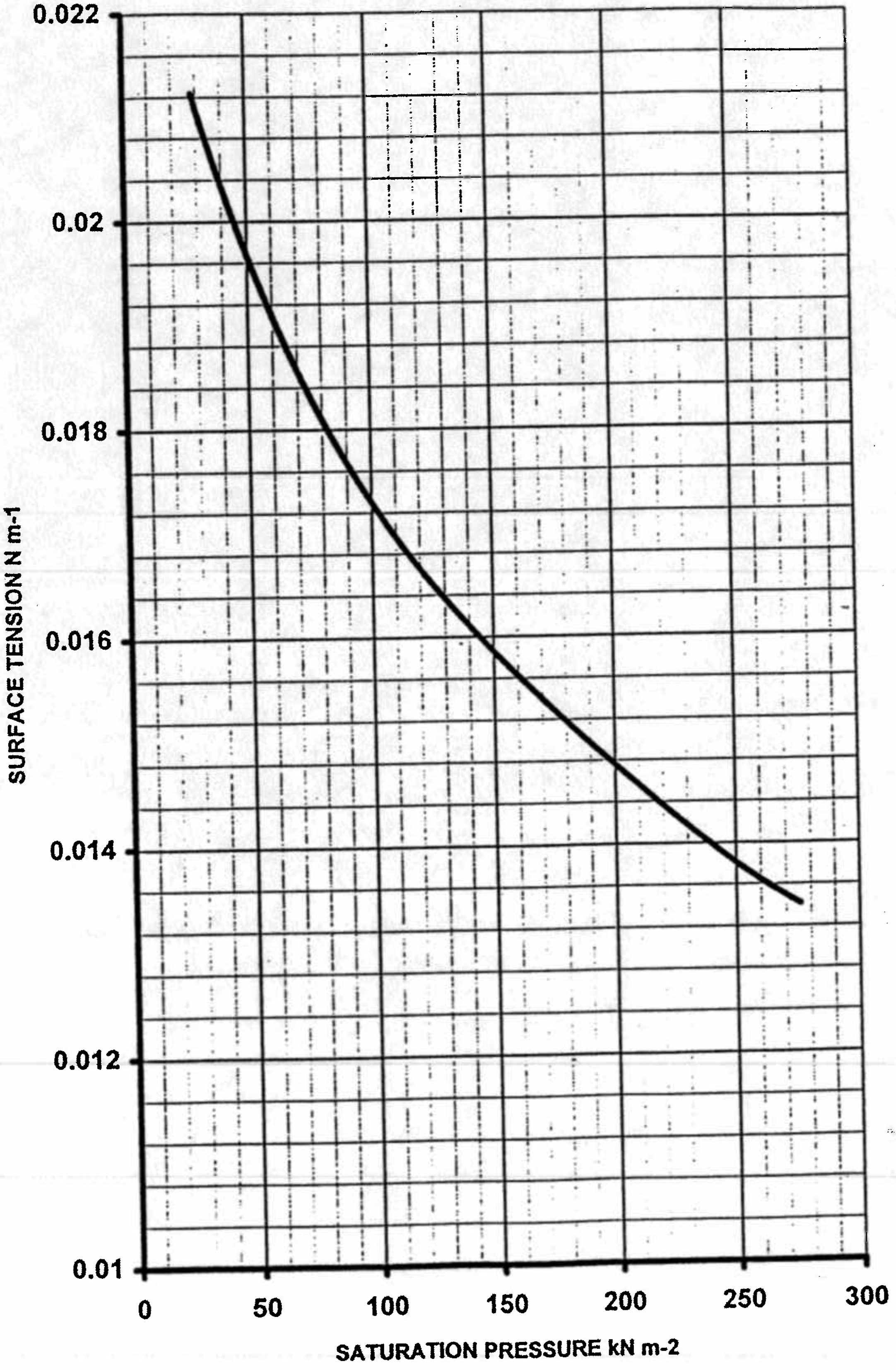


GRAPH 3

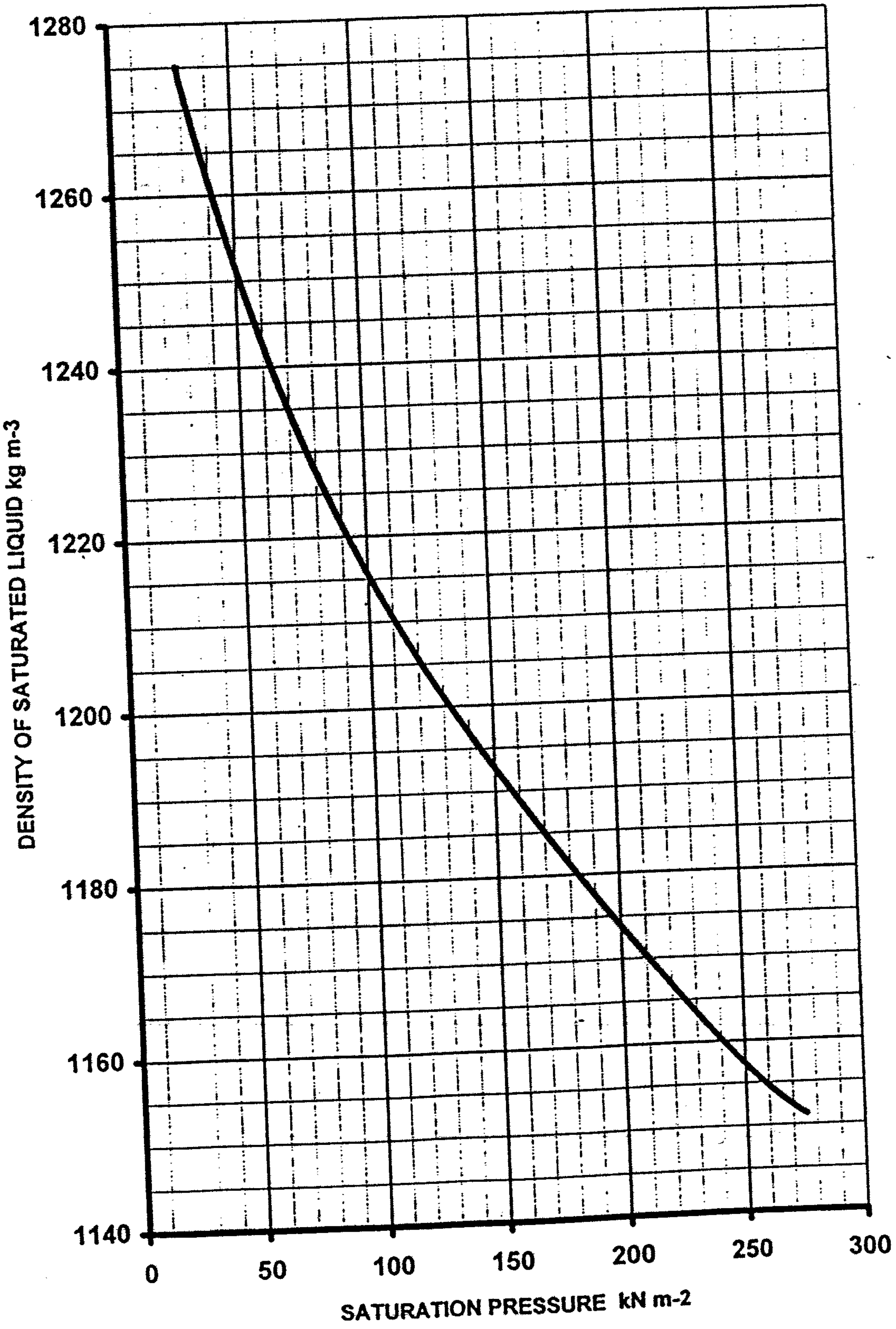
SATURATION TEMPERATURE v. SATURATION PRESSURE FOR R141b



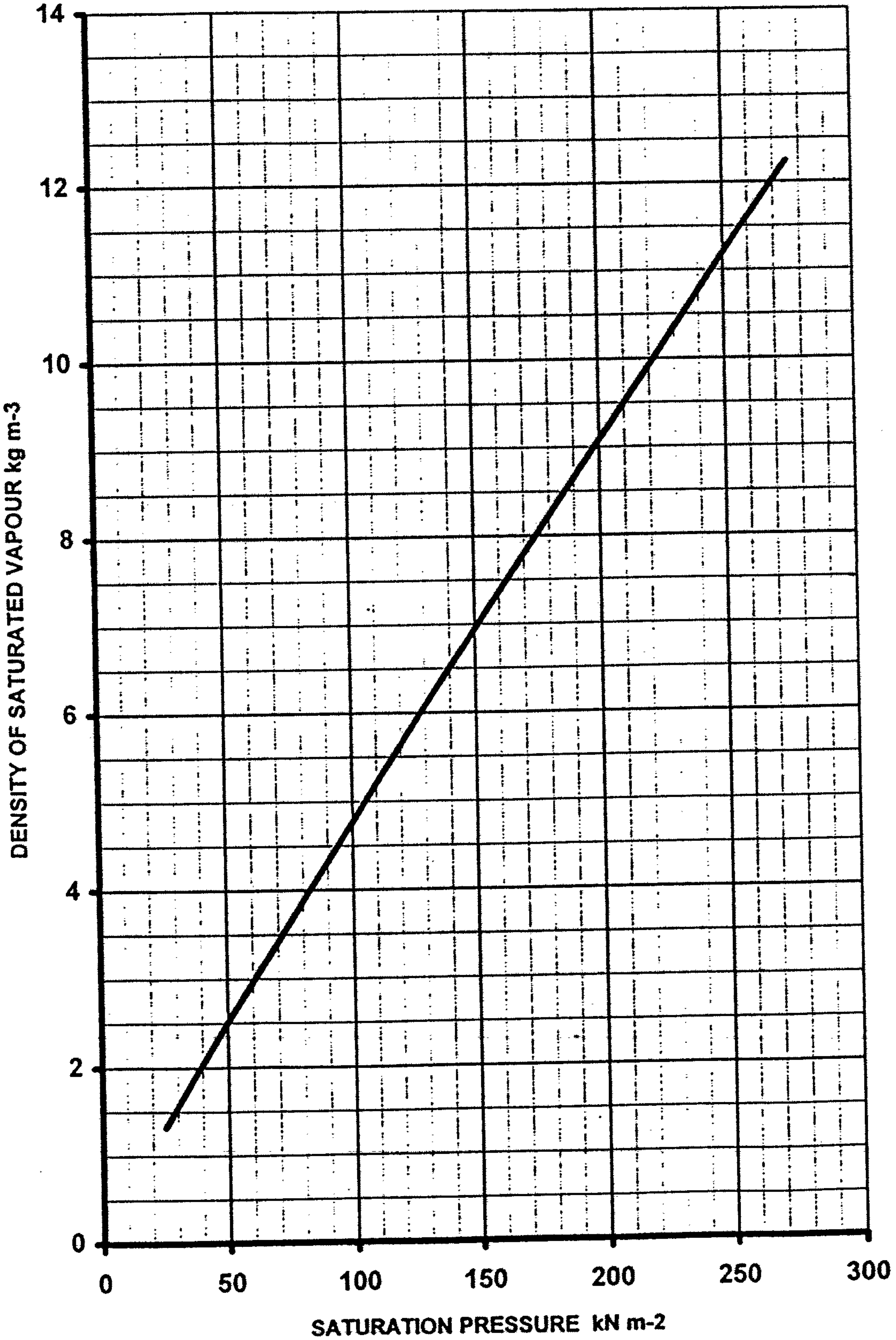
SURFACE TENSION v. SATURATION PRESSURE FOR R141b



DENSITY OF SATURATED LIQUID v. SATURATION PRESSURE FOR R141b



DENSITY OF SATURATED VAPOUR v. SATURATION PRESSURE FOR R141b



LATENT HEAT OF EVAPORATION v. SATURATION PRESSURE FOR R141b