



BSI Standards Publication

Space Engineering — Thermal design handbook

Part 8: Heat Pipes

National foreword

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European Foreword

This document (CEN/CLC/TR 17603-31-08:2021) has been prepared by Technical Committee CEN/CLC/JTC 5 “Space”, the secretariat of which is held by DIN.

It is highlighted that this technical report does not contain any requirement but only collection of data or descriptions and guidelines about how to organize and perform the work in support of EN 16603-31.

This Technical report (TR 17603-31-08:2021) originates from ECSS-E-HB-31-01 Part 8A.

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This document has been prepared under a mandate given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any TR covering the same scope but with a wider domain of applicability (e.g.: aerospace).

1

Scope

Heat pipes are a solution to many thermal dissipation problems encountered in space systems.

The types of heat pipes that can be used in spacecrafts are described. Details on design and construction, usability, compatibility and the limitations of each type are given.

The Thermal design handbook is published in 16 Parts

TR 17603-31-01	Thermal design handbook – Part 1: View factors
TR 17603-31-02	Thermal design handbook – Part 2: Holes, Grooves and Cavities
TR 17603-31-03	Thermal design handbook – Part 3: Spacecraft Surface Temperature
TR 17603-31-04	Thermal design handbook – Part 4: Conductive Heat Transfer
TR 17603-31-05	Thermal design handbook – Part 5: Structural Materials: Metallic and Composite
TR 17603-31-06	Thermal design handbook – Part 6: Thermal Control Surfaces
TR 17603-31-07	Thermal design handbook – Part 7: Insulations
TR 17603-31-08	Thermal design handbook – Part 8: Heat Pipes
TR 17603-31-09	Thermal design handbook – Part 9: Radiators
TR 17603-31-10	Thermal design handbook – Part 10: Phase – Change Capacitors
TR 17603-31-11	Thermal design handbook – Part 11: Electrical Heating
TR 17603-31-12	Thermal design handbook – Part 12: Louvers
TR 17603-31-13	Thermal design handbook – Part 13: Fluid Loops
TR 17603-31-14	Thermal design handbook – Part 14: Cryogenic Cooling
TR 17603-31-15	Thermal design handbook – Part 15: Existing Satellites
TR 17603-31-16	Thermal design handbook – Part 16: Thermal Protection System

2 References

EN Reference	Reference in text	Title
EN 16603-00-01	ECSS-S-ST-00-01	ECSS System - Glossary of terms
TR 17603-31-10	ECSS-E-HB-31-01 Part 10	Thermal design handbook – Part 10: Phase-Change Capacitors
TR 17603-31-13	ECSS-E-HB-31-01 Part 13	Thermal design handbook – Part 13: Fluid Loops
TR 17603-31-14	ECSS-E-HB-31-01 Part 14	Thermal design handbook – Part 14: Cryogenic Cooling

All other references made to publications in this Part are listed, alphabetically, in the **Bibliography**.

Terms, definitions and symbols

3.1 Terms and definitions

For the purpose of this Standard, the terms and definitions given in ECSS-S-ST-00-01 apply.

3.2 Symbols

A_v	vapour core cross-sectional area, [m ²]
A_w	wick cross-sectional area, [m ²].
C	heat pipe thermal conductance, [W.K ⁻¹]
C_i	heat capacity associated to node i , [J.K ⁻¹]
D_i	inner wall diameter of the pipe, [m]
D_o	outer wall diameter of the pipe, [m]
D_p	diameter of particles, [m]
D_v	diameter of the vapour space, [m]
H	equilibrium capillary height, [m]
H_{ij}	heat transfer coefficient between nodes i and j , [W.K ⁻¹]
K	permeability, [m ²]
M	molar mass, [kg.mol ⁻¹]
N	figure of merit, [W.m ⁻²] $N = \rho_l h_{fg} \sigma / \mu_l$
Q	heat transfer rate, [W]
$(Q.l_{eff})$	integral heat transport factor, [W.m]
R	universal gas constant, $R = 8,3143 \text{ J.K}^{-1}.\text{mol}^{-1}$
R_g	gas constant of a particular gas, [J.K ⁻¹ .kg ⁻¹] $R_g = R/M$
Re	Reynolds number, $Re = \rho V D_i / \mu$

T	temperature, [K]
T_s	sink temperature, [K]
ΔT	Clause 5: radial temperature drop between vapour-liquid interface and heat pipe wall, [K] Clause 8: control temperature range of a VCHP, [K] Clause 10: axial temperature drop, [K]
V	Clause 7: velocity, [m.s ⁻¹] Clause 8: volume, [m ³]
We	Weber number, $We = \rho_v(V_v)^2 l' / \sigma$
a	velocity of sound, [m.s ⁻¹]
b	dimensionless constant of a capillary structure, see clause 7.2.1.1
g	acceleration due to gravity, [m.s ⁻²]
h	heat transfer coefficient of the wick, [W.m ⁻² .K ⁻¹]
h_{fg}	latent heat of vaporization, [J.kg ⁻¹]
k	thermal conductivity, [W.m ⁻¹ .K ⁻¹]
k_{eff}	effective thermal conductivity of the wick, [W.m ⁻¹ .K ⁻¹]
k_w	thermal conductivity of the wick material, [W.m ⁻¹ .K ⁻¹]
l	length, [m]
l'	characteristic length associated with the wick surface, [m] it is used to define the Weber number
l_{eff}	effective heat pipe length, [m] $l_{eff} = l_A + (l_C + l_E)/2$
l_w	wick length, [m]
m	mass flow rate. [kg.s ⁻¹]
$\dot{m}$	mass flow rate per unit area, [kg.m ⁻² .s ⁻¹] it is also called mass flux
n	number of moles
p	pressure, [Pa]
p_a	standard atmospheric pressure, $p_a = 1,01325 \times 10^5$ Pa
Δp	pressure drop, [Pa]

Δp_c	capillary pumping pressure, [Pa]
q	radial heat flux, [W.m ⁻²]
r	radius, [m]
r_b	radius of bubble nucleus, [m]
r_c	effective pore radius of the capillary structure, [m]
t	Time, [h]
w	groove width, [m]
w'	fin thickness, [m]
x	coordinate along heat pipe, [m] it is measured from the evaporator
Π	wetted perimeter of a duct, [m]
Φ	wick porosity
γ	vapor specific heat ratio
δ	wick thickness or groove depth, [m]
θ	wetting angle, [angular degrees]
θ_E	wetting angle in the evaporator, [angular degrees]
μ	dynamic viscosity, [Pa.s]
ν	Clauses 5 and 7: liquid to wick material thermal conductivity ratio Clause 10: kinematic viscosity, [m ² .s ⁻¹]
π_r	dimensionless pressure ratio
ρ	density, [kg.m ⁻³]
σ	surface tension, [N.m ⁻¹]
τ	shear stress, [Pa]
φ	tilting angle, [angular degrees], positive when the evaporator is up
ψ	geometrical parameter, it is defined in clause 11.2.1.2

Subscripts

A	adiabatic
C	condenser
E	evaporator
R	reservoir
b	normal boiling conditions
c	Clause 6: thermodynamic critical conditions
	Clause 7: capillary
	Clause 10: superfluid dynamics critical conditions
eff	effective
f	freezing conditions
i	inner wall
l	liquid phase
max	maximum
min	minimum
o	Clause 6: reference temperature conditions
	Clauses 7, 8 and 10: outer wall
sat	saturation conditions
v	vapour phase
w	wick material
λ	helium-4 conditions at the Lambda point

Other symbols, mainly used to define the geometry of the configuration, are introduced when required.

General introduction

The heat pipe is a thermal device which affords an efficient transport of thermal energy. It is constituted by a closed structure containing a working fluid which transfers the thermal energy from one part (evaporator) to another (condenser). The phenomena involved in the transfer process are the following:

1. Vaporization in the evaporator;
2. vapor flow in the core region of the container;
3. condensation in the condenser, and
4. liquid return to the evaporator by capillary action in the wick.

The capillary pumping permits to the heat pipe to be operated in any orientation, in contrast to evaporation cooling devices which can only work when the evaporator is placed at the lowest point of the system.

The pressure variations in the vapor core are normally small and, therefore, the heat pipe temperature is nearly uniform and close to the saturated vapor temperature corresponding to the vapor pressure. The capability of transporting large amounts of thermal energy between two terminals (evaporator and condenser) with a small temperature difference is the main characteristic of the heat pipe which can be considered an extra-high thermal conductivity device in the Fourier's law sense.

In addition to its superior heat transfer characteristics, the heat pipe is structurally simple, relatively inexpensive, insensitive to the gravitational field, and silent and reliable in its operation. It can be made into different shapes and, by using the working fluid best suited to the desired temperature range, can operate at temperature ranging from the cryogenic regions up to high temperature levels which are only limited by structural reasons.

Because the immense potential of heat pipes, they have been employed in many engineering applications, spacecraft thermal control not being an exception.

Classical papers concerning heat pipes are those by Grover et al. (1964) [32] and Cotter (1965) [18]. A presentation of the background required by those wishing to use or to design heat pipes has been made by Dunn & Reay (1976) [21].

Several examples of application of heat pipes to spacecraft are given in the following:

1. It is well known that large temperature variations may occur in the surface of a spacecraft because non-uniform heating. These temperature variations can cause a host of problems including undesirable thermal stresses. Katzoff (1967) [39] has recommended the use of long heat pipes wrapped around the outer surface of a spacecraft to accomplish the necessary equalization of the temperature distribution.
2. Another application which has received considerable attention is the cooling of electronic components of spacecraft systems. These components are often located in the interior of

the satellite, and the aim of the heat pipe is to transfer the waste heat over some distance for ultimate rejection to outer space.

3. The use of radiators formed by heat pipes has been suggested several times. The heat pipes produce nearly uniform temperatures on the radiator surface, and the redundancy achieved when used in parallel arrangement provides some degree of increased meteor protection to the radiator.

Intensive heat pipe research and development have resulted in rapid advancement in a variety of directions: from the simple cylindrical shape to complex geometries; from a screen mesh to multicomponent capillary-wick structures; from a passive variable-temperature conduction link to self-controlled, variable-conductance, constant-temperature devices, and from the high conductance function to a multitude of thermal control functions (such as switching, transformer, diode, and damping, among others). Considerable progress has been made in material compatibility, fabrication technology, and operational handling.

Since the heat pipe is both lightweight and nearly isothermal it appears to provide ideal solutions to many thermal dissipation problems encountered in spacecraft.

Heat pipe wicks

5.1 General

The heat pipe utilized for its operation capillary induced fluid flow, instead of gravitational or mechanical work. This particular feature has led to considerable research efforts aimed at developing wick materials suitable for use as capillary pumping devices in heat pipes.

The primary requisite for a heat pipe wick is that it should act as an effective capillary pump. That is, the surface tension forces developed between the fluid and the wick structure should be sufficient to overcome all viscous and other pressure drops in the pipe, still maintaining the required fluid circulation.

In addition to the operating characteristics, several mechanical features should be considered when evaluating candidate heat pipe wicks. The wick should be mechanically stable and rigid enough to avoid changing of flow properties in response to wick sagging or stretching. On the other hand, the suitable wick material should be compatible with the working fluid used. Many of the problems associated with long term heat pipe operation are a direct consequence of material incompatibility which usually manifests itself in chemical reactions.

A wide variety of wicks has been successfully employed in heat pipes. The first, and still the most widely used, consists of several layers of fine mesh screen. Different methods have been used to assure mechanical contact between the screen and the container. The reader is referred for further details to: Neal (1967) [63], Katzoff (1967) [39], Kemme (1968) [41], and McKinney (1969) [58], among others.

Screens have been also used merely as a retaining structure for wicks consisting in various types of beads packed in an annulus between the retaining screen and the pipe wall. Beads of Monel, glass, and stainless steel of different diameters have been used to produce these wicks.

Textile fabrics have also been employed as wicks. Rayon cloth has been used for a nitrogen heat pipe (Haskin (1967) [33]). The cloth was held firmly against the heat pipe wall by sliding together two valves of a slotted, diagonally cut retaining tube. Commercially available quartz fiber cloth has been used as wick for flexible heat pipes (Shlosinger et al. (1966) [87]). In these devices the cloth was pressed against the wall with springs. Attempts to bond the cloth to the wall met only with limited success. A good bonding was achieved by applying heat sealable film materials, such as thermosetting and thermoplastic sheets of the polyester resins.

Other investigators have experimented with commercially available porous metals, using sintered fiber wicks (Neal (1967) [63]).

In addition, wicks have been successfully fabricated from powders of Al_2O_3 , SiC, Al, Cu, and Ni.

5.2 Basic properties

The properties which characterize the behavior of heat pipe wicks are: equilibrium capillary height, permeability, and effective thermal conductivity.

5.2.1 Equilibrium capillary height

Equilibrium capillary height, H , is the maximum height to which a wick lifts a given fluid. Two considerations underline the importance of this variable for heat pipe design. First, the value of H limits the length of a heat pipe operating in a gravity field with the evaporator above the condenser. Second, H is used for evaluating the capillary pumping capability of a candidate wick. Once H has been determined, both the effective pore radius of the capillary structure, r_c , and the capillary pumping pressure, Δp_c , can be calculated (see Winter and Barsch (1971) [96])

$$r_c = (2\sigma \cos\theta) / (\rho_l g H),$$

$$\Delta p_c = 2\sigma / r_c.$$

Two different values of the capillary height can be measured in a porous structure: the rising value (wick initially dry) and the falling value (wick initially saturated). In general, the height to which a liquid will rise in a wick (rising height) is less, by approximately 25% (Katzoff (1967) [39]), than the height to which the liquid will fall in the same wick after it has been completely soaked (falling height).

5.2.2 Permeability

The permeability, K , of a porous body is the proportionality constant between mass flow rate and pressure drop (see Eq. (7.33), [ECSS-E-HB-31-01 Part 14, clause 7.4.2.4](#)). K has the dimension of an area and can be expressed by the following relationship (Ferrel & Johnson (1970) [26])

$$K = \frac{\mu_l \frac{Q}{h_{fg} \rho_l A_w}}{\Delta p_l / l_w} \quad [5-1]$$

Note: non-si units are used in this figure

The permeability depends on the dimensions and geometry of the passages in the wick, and can be experimentally determined by measuring the pressure drop which experiences a given mass flow rate of a liquid flowing through the wick.

5.2.3 Effective thermal conductivity of the wick

The thermal energy required for vaporization (or condensation) is transferred by conduction, through the saturated wick, from the solid boundary surfaces to the liquid-vapor interface. Thence the effective thermal conductivity, k_{eff} , of the liquid saturated wick should be as large as possible.

The radial temperature drop between the liquid-vapor interface and the wall of the pipe can be calculated from the following expression (Grant (1973) [28]):

$$\Delta T = qD_i \left[\frac{\ln \frac{D_o}{D_i}}{2k_w} + \frac{\ln \frac{D_i}{D_v}}{2k_{eff}} \right] \quad [5-2]$$

Note: non-si units are used in this figure

Table 5-1 gives formulae for calculating the three wick properties which have been mentioned.

Table 5-1: Empirical Correlations for the Determination of Wick Properties

WICK PROPERTY	FORMULA	COMMENTS	Reference
Equilibrium Capillary Height, H.	$H = \frac{4\sigma}{0.41D_p\rho_l g}$ <p>Note: non-si units are used in this figure</p>	The pore diameter, 0,41 D _p , corresponds to the largest minimum pore diameter existing in a cubic array of a randomly packed bed of spheres.	Ferrel & Alleavitch (1970) [25]
Permeability, K.	$K = \frac{D_p^2 \Phi^3}{150(1-\Phi)^2}$ <p>Note: non-si units are used in this figure</p>	Correlation between K and D _p is not very appropriate. Unfortunately no correlation exists, up to the moment, between K and more easily measurable wick characteristics.	Bird, Stewart & Lightfoot (1960) [10]
Dimensionless Effective Thermal Conductivity, k_{eff}/k_w .	$\frac{k_{eff}}{k_w} = (1-\Phi) + \nu\Phi$ <p>Note: non-si units are used in this figure</p>	It is assumed that the thermal conduction paths through liquid and through screen wick are parallel.	Neal (1967) [63], Kunz et al. (1968) [46]
	$\frac{k_{eff}}{k_w} = \frac{\nu}{\nu + \Phi(1-\nu)}$ <p>Note: non-si units are used in this figure</p>	It is assumed that the thermal conduction paths through liquid and through screen wick are in series.	Joy (1970) [38]
	$\frac{k_{eff}}{k_w} = \left(\frac{k_{eff}}{k_w} \right)_{drv} + \nu\Phi$ <p>Note: non-si units are used in this figure</p>	It is assumed that the thermal conduction paths through liquid and through screen wick are parallel.	Woo (1968) [97]

WICK PROPERTY	FORMULA	COMMENTS	Reference
	$\frac{k_{eff}}{k_w} = 0,046(1-\nu)(1-\Phi) + \nu \left[1 + \frac{0,954(1-\nu)(1-\Phi)}{1-(1-\nu)(1-\Phi)^{0,012}} \right]$ $0,65 \leq \Phi \leq 1$ <p>Note: non-si units are used in this figure</p>	Obtained from data concerning water-saturated nickel fiber wicks.	Soliman, Graumann & Berenson (1970) [91]
	$\frac{k_{eff}}{k_w} = 0,13(1-\nu)(1-\Phi) + \nu \left[1 + \frac{0,87(1-\nu)(1-\Phi)}{1-(1-\nu)(1-\Phi)^{0,006}} \right]$ $0,65 \leq \Phi \leq 1$	Obtained from data concerning water-saturated copper fiber wicks.	

5.3 Low resistance wicks

In addition to simple screen wicks, which have been already described, considerable attention has been paid to low resistance configurations.

There are three main different types of low resistance wicks.

1. Grooved heat pipes, with channels running axially along the inner surface of the tube. These configurations are structurally stable, have a large pipe wall to wick thermal conductance, and allow an ease control of pore size during manufacturing.
2. Composite wicks have been advocated by Kemme (1968) [41]. These wicks combine a material with fine pore size at the liquid vapor interface, with a larger pore size material underneath. The aim of the fine pores is to enhance the capillary effect, while the larger pores are introduced to expedite the return of the liquid.

Composite wicks may be manufactured either by combining screens of different mesh sizes, or by covering grooves which have been cut along the walls with a fine mesh size screen.

3. The condensed liquid can be delivered to the evaporator through one or more nearly cylindrical arteries, which are placed in the vicinity of the pipe center-line, and are extensions of the wick covering the inner wall of the pipe. This idea was set forth by Katzoff (1967) [39].

Table 5-2 in the following pages gives relevant properties for several combinations of wicking materials and working fluids.

Table 5-2: Properties of Wick Materials

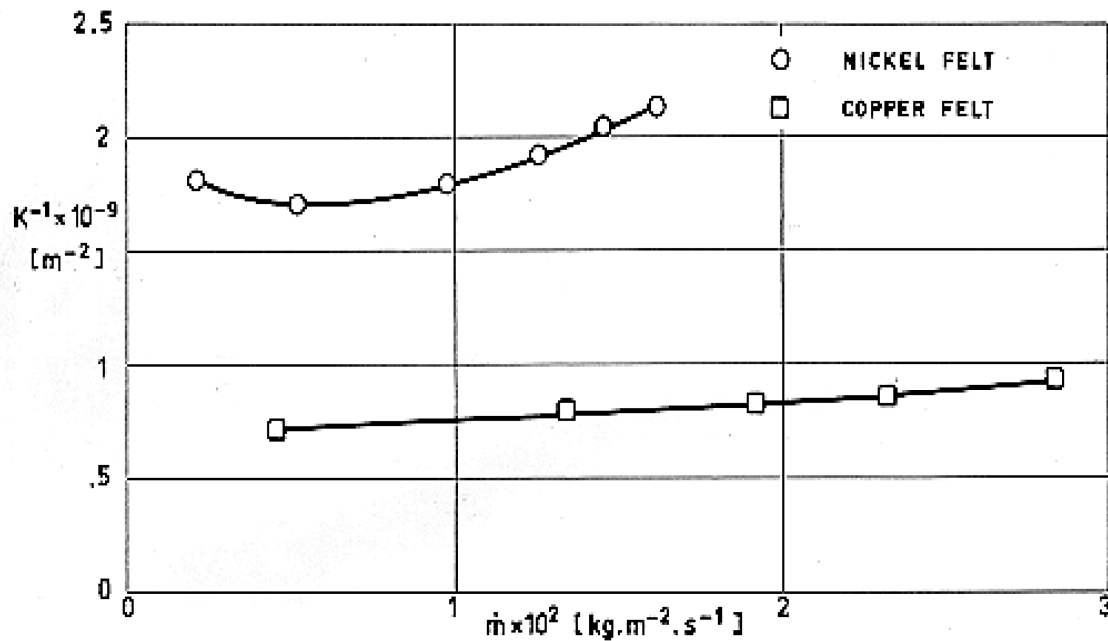
Wick Material (Supplier)	Fluid	Geometrical Characteristics	Φ	H [m]	$r_c \times 10^4$ [m]	$K \times 10^{10}$ [m ²]	k_{eff} [W.m ⁻¹ .K ⁻¹]		Ref.
							Dry	Saturated	
Bronze Mesh Screen	Methanol	Mesh Size = 74×10^{-6} m			0,535				f
	Water	Mesh Size = 74×10^{-6} m			0,61				g
Copper Sintered Powder $0,51 \times 10^{-3}$ m. Copper Backing. ^a	Water	$\delta = 0,79 \times 10^{-3}$ m	0,62	0,872		0,05			h
	Water	$\delta = 0,79 \times 10^{-3}$ m	0,70	0,816		0,06			
Copper Sintered Powder ^a	Water	$\delta = 1,3 \times 10^{-3}$ m	0,57	0,853		0,056	21,8	41,2	
Copper Felted Metal ^b	Benzene	$\delta = 2,5 \times 10^{-3}$ m	0,89		2,3	Figure 5-1			f
	Methanol	$\delta = 2,5 \times 10^{-3}$ m	0,89		2,15				
	Water	$\delta = 2,5 \times 10^{-3}$ m	0,89		2,8				
Copper Felted Metal ^c	Water	$\delta = 1,6 \times 10^{-3}$ m	0,59	0,311		0,43	22,3	78,3	
Copper Foam Amporcop 210-5 ^b	Benzene	$\delta = 0,46 \times 10^{-3}$ m	0,94		4,6				
	Methanol								
	Water	$\delta = 0,46 \times 10^{-3}$ m	0,94		4,3	Figure 5-2			
Copper Foam Amporcop 220-5 ^b	Water	$\delta = 2,6 \times 10^{-3}$ m	0,91		4,8				
Nickel Mesh Screen	Water	Mesh Size = 297×10^{-6} m	0,625	0,049		6,64			i
		Mesh Size = 74×10^{-6} m	0,679	0,112		1,52			
		Mesh Size = 74×10^{-6} m	0,676	0,234		0,77			

Wick Material (Supplier)	Fluid	Geometrical Characteristics	Φ	H [m]	$r_c \times 10^4$ [m]	$K \times 10^{10}$ [m ²]	k_{eff} [W.m ⁻¹ .K ⁻¹]		Ref.
							Dry	Saturated	
Nickel Powder	Freon 113	Powder Size Range = 297×10^{-6} – 841×10^{-6} m.	0,54	0,178		0,81			
	Freon 113	Powder Size Range = 297×10^{-6} – 841×10^{-6} m.	0,696	0,051		3			
	Water	Powder Size Range = 150×10^{-6} – 297×10^{-6} m.	0,658	0,247		2,73			
	Water	Powder Size Range = 297×10^{-6} – 841×10^{-6} m.	0,54	0,406		0,81			
	Water	Powder Size Range = 297×10^{-6} – 841×10^{-6} m.	0,696	0,175		3			
Nickel Fiber	Freon 113	Fiber Diameter = 10^{-5} m.	0,868	0,107		0,44			
	Freon 113	Fiber Diameter = 10^{-5} m.	0,825	0,125		0,34			
	Freon 113	Fiber Diameter = 10^{-5} m.	0,689	0,209		0,15			
	Freon 113	Fiber Diameter = $1,5 \times 10^{-5}$ m.	0,88	0,09		0,31			
	Water	Fiber Diameter = 10^{-5} m.	0,868	0,404		0,44			
	Water	Fiber Diameter = 10^{-5} m.	0,825	0,406		0,34			
	Water	Fiber Diameter = 10^{-5} m.	0,689	0,406		0,15			
	Water	Fiber Diameter = $1,5 \times 10^{-5}$ m.	0,88	0,399		0,31			

Wick Material (Supplier)	Fluid	Geometrical Characteristics	Φ	H [m]	$r_c \times 10^4$ [m]	$K \times 10^{10}$ [m ²]	k_{eff} [W.m ⁻¹ .K ⁻¹]		Ref.
							Dry	Saturated	
Nickel Felted Metals ^c	Water	$\delta = 1,9 \times 10^{-3}$ m	0,82	0,292		0,6	2,97	5,5	h
	Water	$\delta = 2,1 \times 10^{-3}$ m	0,61	0,582		0,08	16,6	26,3	
Nickel Felted Metals ^b	Water	$\delta = 2,5 \times 10^{-3}$ m	0,89		1,65	Figure 5-1			f
Nickel Foam Ampornick 220-5 ^b	Benzene	$\delta = 2,5 \times 10^{-3}$ m	0,96		2,1	Figure 5-2			
	Methanol	$\delta = 2,5 \times 10^{-3}$ m	0,96		2,6				
	Water	$\delta = 2,6 \times 10^{-3}$ m	0,96		2,3				
Nickel Foam Ampornick 210-5 ^b	Water	$\delta = 2,6 \times 10^{-3}$ m	0,94		2,3				
Stainless Steel Mesh Screen ^d	Benzene	Mesh Size = 74×10^{-6} m $\delta = 0,89 \times 10^{-4}$ m	0,73		0,57				h
	Methanol	Mesh Size = 74×10^{-6} m $\delta = 0,89 \times 10^{-4}$ m	0,73		0,54				
	Water	Mesh Size = 74×10^{-6} m $\delta = 0,89 \times 10^{-4}$ m	0,73		0,58				
Stainless Steel Mesh Screen ^e	Water	Mesh Size = 420×10^{-6} m 6 layers	0,69	0,054		3,7	0,692	3,86	h
	Water	Mesh Size = 149×10^{-6} m 10 layers	0,63	0,109		2,1	0,692	4,5	
	Water	Mesh Size = 111×10^{-6} m 22 layers	0,68	0,143		0,8	0,657	3,51	
	Water	Mesh Size = 74×10^{-6} m 32 layers	0,69	0,199		0,54			
Stainless	Water	$\delta = 2,8 \times 10^{-3}$ m	0,32	1,02		0,049	3,04	11,4	

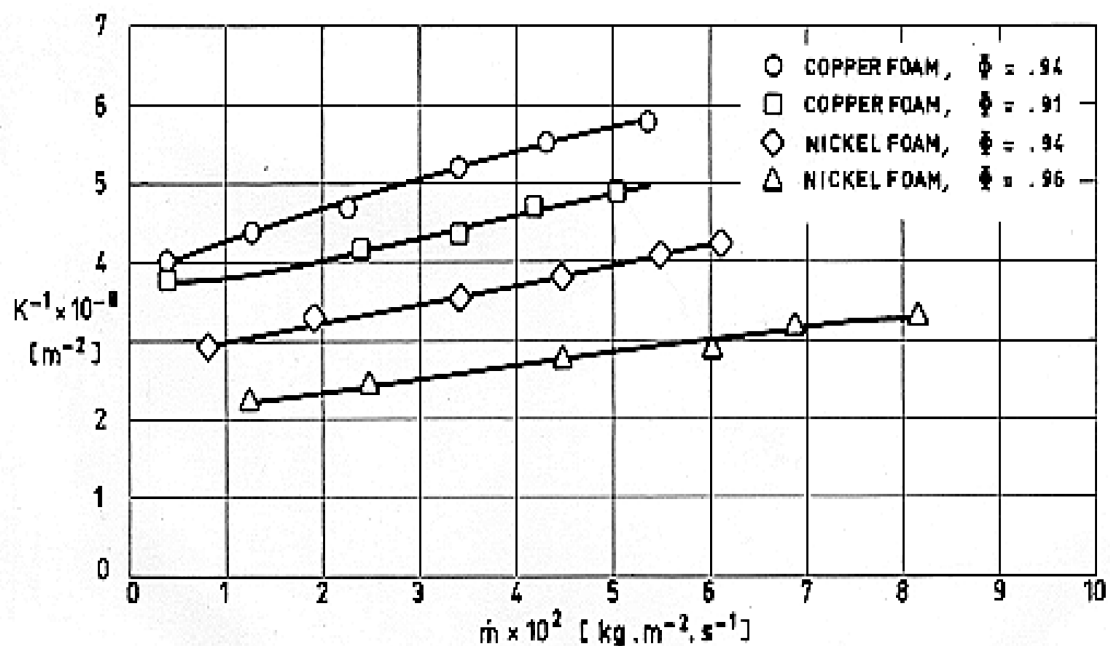
Wick Material (Supplier)	Fluid	Geometrical Characteristics	Φ	H [m]	$r_c \times 10^4$ [m]	$K \times 10^{10}$ [m ²]	k_{eff} [W.m ⁻¹ .K ⁻¹]		Ref.
							Dry	Saturated	
Steel Sintered Powder ^e	Water	$\delta = 2,8 \times 10^{-3}$ m	0,47	0,539		0,16	2,06	6,88	
	Water	$\delta = 2,8 \times 10^{-3}$ m	0,57	0,304		0,42	2,21	6,04	
Stainless Steel Fiber Materials (SS-430)	Water	Fiber Diameter = $3,3 \times 10^{-5}$ m	0,916	0,155		5,46			i
	Water	Fiber Diameter = $3,3 \times 10^{-5}$ m	0,808	0,227		1,96			
	Water	Fiber Diameter = $7,6 \times 10^{-5}$ m	0,822	0,135		11,61			
Stainless Steel Felted Metals ^c	Water	$\delta = 3 \times 10^{-3}$ m	0,89	0,067		5,96	0,74	2,45	h
	Water	$\delta = 3,2 \times 10^{-3}$ m	0,80	0,119		2,69	1,18	3,27	
	Water	$\delta = 3,2 \times 10^{-3}$ m	0,58	0,256		0,54	4,2	9,6	

^a Gold Inc.^b Astro Met Associates Inc.^c Huyck Metals Co.^d Michigan Wire Cloth Co.^e Gerard Daniel & Co.^f Phillips & Hinderman (1969) [67]^g Katzoff (1967) [39]^h Ferrel, Alexander & Piver (1973) [24]ⁱ Langston & Kunz (1969) [48]



Note: non-si units are used in this figure

Figure 5-1: Measured values of the inverse permeability, K^{-1} , vs. mass flow rate per unit area, $\dot{m}$.> From Phillips & Hinderman (1969) [67].



Note: non-si units are used in this figure

Figure 5-2: Measured values of the inverse permeability, K^{-1} , vs. mass flow rate per unit area, $\dot{m}$.> From Phillips & Hinderman (1969) [67].

Heat pipe working fluids

6.1 General

A wide variety of fluids ranging from cryogenics to liquid metals have been used as heat pipe working fluids.

The choice of a working fluid for a heat pipe application is dictated to a large extent by several physical properties of the fluid and by chemical compatibility of the fluid with the container and the wick. The requirements which should be taken into account when selecting a heat pipe working fluid are the following:

1. High latent heat of vaporization.
2. High thermal conductivity.
3. Low viscosity.
4. High surface tension.
5. High wetting ability.
6. Boiling point suited to the required operating temperature.

In order to minimize the temperature change associated to a given pressure drop, the fluids should be used in a steeply sloped region of its vapor pressure-temperature curve.

The ranking of the working fluids within a particular temperature range is usually established by means of a dimensional fluid property group, named figure of merit, which has dimensions of heat flux [W.m^{-2}], and is defined as:

$$N = \rho h_{fg} \sigma / \mu_l$$

Relevant physical properties of suitable heat pipe working fluids are presented in this clause. These properties are:

1. Vapour Pressure, p_{sat} . [Pa].
2. Latent Heat of Vaporization, h_{fg} . [J.kg^{-1}].
3. Density of Liquid Phase, ρ_l . [kg.m^{-3}].
4. Density of Vapor Phase, ρ_v . [kg.m^{-3}].
5. Dynamic Viscosity of Liquid Phase, μ_l . [Pa.s].
6. Dynamic Viscosity of Vapor Phase, μ_v . [Pa.s].
7. Thermal Conductivity of Liquid Phase, k_l . [$\text{W.m}^{-1}\text{.K}^{-1}$].
8. Thermal Conductivity of Vapor Phase, k_v . [$\text{W.m}^{-1}\text{.K}^{-1}$].
9. Surface Tension, σ . [N.m^{-1}].

10. Figure of Merit, N . [W.m^{-2}].

The mathematical expressions used for the evaluation of these properties have been summarized in Clause 6.2. The resulting values of the mentioned properties have been presented in graphical form in Clause 6.3.

6.2 Empirical correlations

The following expressions have been used for the numerical calculation of the relevant physical properties of heat pipe working fluids. Additional details can be found in books like Reid & Sherwood (1966) [70]. Sources of experimental data are indicated in the sheets concerning the different fluids.

- Vapour Pressure, p_{sat} . [Pa], Riedel-Plank-Miller formula:

$$\log \frac{p_{sat}}{p_c} = -\frac{G}{T/T_c} \left[1 - \left(\frac{T}{T_c} \right)^2 + g \left(1 - \frac{T}{T_c} \right)^3 \left(3 + \frac{T}{T_c} \right) \right] \quad [6-1]$$

Note: non-si units are used in this figure

where

$$G = 0,21 + 0,4605 \frac{T_b}{T_c - T_b} \log \frac{p_c}{p_a} \quad [6-2]$$

Note: non-si units are used in this figure

$$g = \frac{\frac{T_b}{G(T_c - T_b)} \log \frac{p_c}{p_a} - \left(1 + \frac{T_b}{T_c} \right)}{\left(1 - \frac{T_b}{T_c} \right)^2 \left(3 + \frac{T_b}{T_c} \right)} \quad [6-3]$$

Note: non-si units are used in this figure

- Latent Heat of Vaporization, h_{fg} . [J.kg^{-1}], Theisen formula:

$$h_{fg} = H \left(1 - \frac{T}{T_c} \right)^{n_h} \quad [6-4]$$

Note: non-si units are used in this figure

H and n_h are deduced from the experimental data by using the least squares technique.

- Density of Liquid Phase, ρ . [kg.m^{-3}], Benson formula:

$$\rho_l = 2\rho_c - \rho_v + \frac{T_c - T}{T_c - T_b}(\rho_{lb} - 2\rho_c) \quad [6-5]$$

Note: non-si units are used in this figure

- Density of Vapor Phase, ρ_v . [kg.m⁻³], Redlich-Kwong state equation:

$$\left[p + \frac{1,2826 R_g T_c \rho_v^2}{\left(\frac{T}{T_c}\right)^{0,5} (\rho_c + 0,2599 \rho_v)} \right] (\rho_c - 0,2599 \rho_v) = R_g T \rho_v \rho_c \quad [6-6]$$

Note: non-si units are used in this figure

- Dynamic Viscosity of Liquid Phase, μ_l . [Pa.s], Girifalco formula:

$$\mu_l = \exp \left[\sum_0^n A_n T^{-n} \right] \quad [6-7]$$

Note: non-si units are used in this figure

The coefficients A_n are deduced from the experimental data by using the least squares technique.

- Dynamic Viscosity of Vapor Phase, μ_v . [Pa.s], Sutherland formula:

$$\mu_v = \frac{b T^{3/2}}{s + T} \quad [6-8]$$

b and s are deduced from the experimental data by using the least squares technique.

- Thermal Conductivity of Liquid Phase, k_l . [W.m⁻¹.K⁻¹]:

$$k_l = k_{lo} \left[1 + \sum_1^n B_n (T - T_o)^n \right] \quad [6-9]$$

The coefficients B_n are deduced from the experimental data by using the least squares technique.

- Thermal Conductivity of Vapor Phase, k_v . [W.m⁻¹.K⁻¹], Owens-Thodos formula:

$$k_v = K \left(\frac{T}{T_c} \right)^{n_k} \quad [6-10]$$

K and n_k are deduced from the experimental data by using the least squares technique.

- Surface Tension, σ , [N.m⁻¹].

$$\sigma = D \left(1 - \frac{T}{T_c} \right)^{n_\sigma} \quad [6-11]$$

D and n_σ are deduced from the experimental data by using the least squares technique.

6.3 Physical properties

The working fluid properties given in this clause are those listed in Clause 6.2. The fluids are, in order of appearance,

Ammonia

Ethanol

Freon 11

Methanol

Nitrogen

Propane

Water

A sheet dealing with a given fluid is arranged as follows: The available data are summarized in a figure and the particular expressions used to correlated them are presented in the following. The sources of the experimental data presented are given in the table below.

FLUID: AMMONIA	$T_b = 239,8 \text{ K}$	$p_c = 1,1297 \times 10^7 \text{ Pa}$
CHEMICAL SYMBOL: NH ₃	$T_c = 405,6 \text{ K}$	$\rho_c = 235 \text{ kg.m}^{-3}$
MOLAR MASS: 17,032	$T_f = 195,3 \text{ K}$	$\rho_{lb} = 681,8 \text{ kg.m}^{-3}$

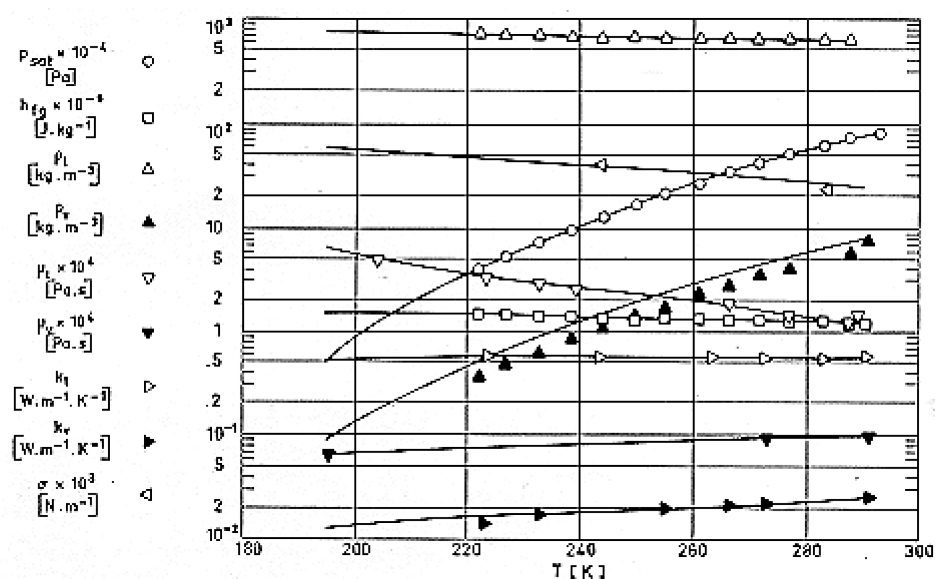


Figure 6-1: Relevant physical properties of Ammonia as a function of temperature, T , The labels correspond to experimental points. The expressions used to calculate the tabulated values are given below. Calculated by the compiler.

Formulae Used for Calculating the Values of the Physical Properties.

$$\log \frac{P_{sat}}{P_c} = -\frac{2,9619}{T/T_c} \left[1 - \left(\frac{T}{T_c} \right)^2 + 0,4843 \left(1 - \frac{T}{T_c} \right)^3 \left(3 + \frac{T}{T_c} \right) \right] \quad [6-12]$$

Note: non-si units are used in this figure

$$h_{fg} = 1,9152 \times 10^6 \left(1 - \frac{T}{T_c} \right)^{0,3737}, \quad 198 < T < 405 \quad [6-13]$$

Note: non-si units are used in this figure

$$\rho_l = 470 - \rho_v + 493,76 \left(1 - \frac{T}{T_c} \right) \quad [6-14]$$

Note: non-si units are used in this figure

$$\left[p + \frac{21760 \rho_v^2}{T^{0,5} (1 + 0,00111 \rho_v)} \right] (1 - 0,00111 \rho_v) = 488,16 T \rho_v \quad [6-15]$$

Note: non-si units are used in this figure

$$\mu_l = 10^{-4} \exp \left[\frac{-19,163 + \frac{12461}{T}}{-\frac{2,6412 \times 10^6}{T^2} + \frac{2,0062 \times 10^8}{T^3}} \right], \quad 204 < T < 405 \quad [6-16]$$

Note: non-si units are used in this figure

$$\mu_v = \frac{1,1989 \times 10^{-6} T^{3/2}}{306 + T}, \quad 195 < T < 405 \quad [6-17]$$

Note: non-si units are used in this figure

$$k_l = 0,547 \left[\frac{1 + 1,1296 \times 10^{-3} (T - 223,2)}{-2,6317 \times 10^{-5} (T - 223,2)^2} \right], \quad 223 < T < 373 \quad [6-18]$$

Note: non-si units are used in this figure

$$k_v = 3,6856 \times 10^{-2} \left(\frac{T}{T_c} \right)^{1,3356}, \quad 223 < T < 400 \quad [6-19]$$

Note: non-si units are used in this figure

$$\sigma = 0,1449 \left(1 - \frac{T}{T_c} \right)^{1,4414}, \quad 244 < T < 405 \quad [6-20]$$

Note: non-si units are used in this figure

Sources of Data.

VARIABLE	REFERENCES
p_{sat}	Weast (1976) [95].
h_{fg}	Raznjevic (1970) [69].
ρ_l	Scollon & Carpitella (1970) [83].
ρ_v	
μ_l	
μ_v	
k_l	
k_v	
σ	Scollon & Carpitella (1970) [83], Weast (1976) [95].

FLUID: ETHANOL

 $T_b = 351,5 \text{ K}$ $p_c = 6,178 \times 10^6 \text{ Pa}$ CHEMICAL SYMBOL: $\text{C}_2\text{H}_6\text{O}$ $T_c = 516,2 \text{ K}$ $\rho_c = 280 \text{ kg.m}^{-3}$

MOLAR MASS: 46,07

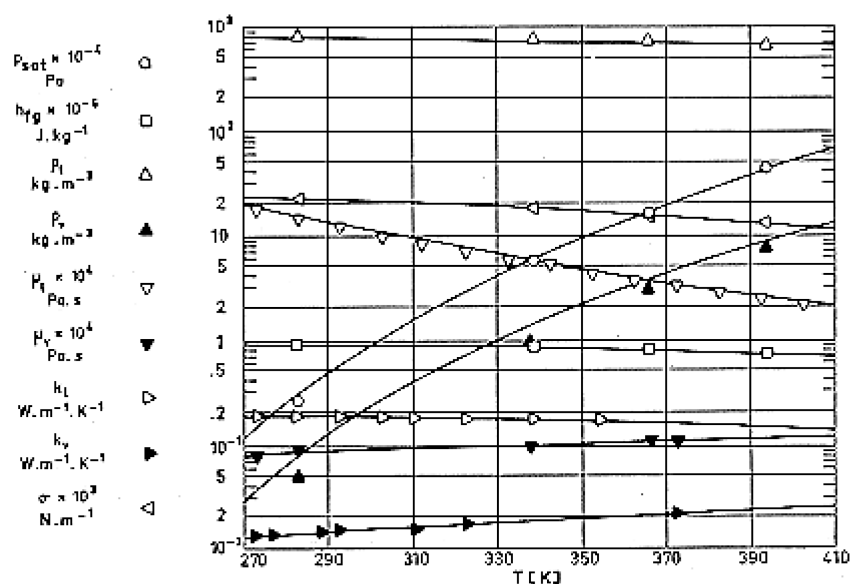
 $T_f = 158,7 \text{ K}$ $\rho_b = 735 \text{ kg.m}^{-3}$ 

Figure 6-2: Relevant physical properties of Ethanol as a function of temperature, T .
The labels correspond to experimental points. The expressions used to calculate the tabulated values are given below. Calculated by the compiler.

Formulae Used for Calculating the Values of the Physical Properties.

$$\log \frac{p_{sat}}{p_c} = -\frac{1,9642}{T/T_c} \left[1 - \left(\frac{T}{T_c} \right)^2 + 0,6896 \left(1 - \frac{T}{T_c} \right)^3 \left(3 + \frac{T}{T_c} \right) \right] \quad [6-21]$$

Note: non-si units are used in this figure

$$h_{fg} = 1,1987 \times 10^6 \left(1 - \frac{T}{T_c} \right)^{0,3218}$$

$$\rho_l = 560 - \rho_v + 548,43 \left(1 - \frac{T}{T_c} \right), \quad 283 < T < 516 \quad [6-22]$$

Note: non-si units are used in this figure

$$\left[p + \frac{9694 \rho_v^2}{T^{0,5} (1 + 0,000928 \rho_v)} \right] (1 - 0,000928 \rho_v) = 180,47 T \rho_v \quad [6-23]$$

Note: non-si units are used in this figure

$$\mu_l = 10^{-4} \exp \left[-6,7461 + \frac{4276,4}{T} - \frac{6,0983 \times 10^5}{T^2} + \frac{4,4784 \times 10^7}{T^3} \right], \quad 173 < T < 423$$

$$\mu_v = \frac{8,6287 \times 10^{-7} T^{3/2}}{188 + T}, \quad 263 < T < 473 \quad [6-24]$$

$$k_l = 0,185 \left[1 + 2,5253 \times 10^{-4} (T - 272) - \frac{1,4539 \times 10^{-6} (T - 272)^2}{2} \right], \quad 273 < T < 355$$

Note: non-si units are used in this figure

$$k_v = 3,5592 \times 10^{-2} \left(\frac{T}{T_c} \right)^{1,5837}, \quad 266 < T < 348$$

$$\sigma = 0,0468 \left(1 - \frac{T}{T_c} \right)^{0,8612}, \quad 283 < T < 516 \quad [6-25]$$

Sources of Data.

VARIABLE	REFERENCES
p _{sat}	Scollon & Carpitella (1970) [83].
h _{fg}	
ρ _l	
ρ _v	
μ _l	Raznjevic (1970) [69].
μ _v	Scollon & Carpitella (1970) [83].
k _l	
k _v	
σ	Scollon & Carpitella (1970) [83]; Weast (1976) [95].

FLUID: FREON 11

 $T_b = 296 \text{ K}$ $p_c = 4,374 \times 10^6 \text{ Pa}$ CHEMICAL SYMBOL: CF Cl_3 $T_c = 471,2 \text{ K}$ $\rho_c = 555 \text{ kg.m}^{-3}$

MOLAR MASS: 137,38

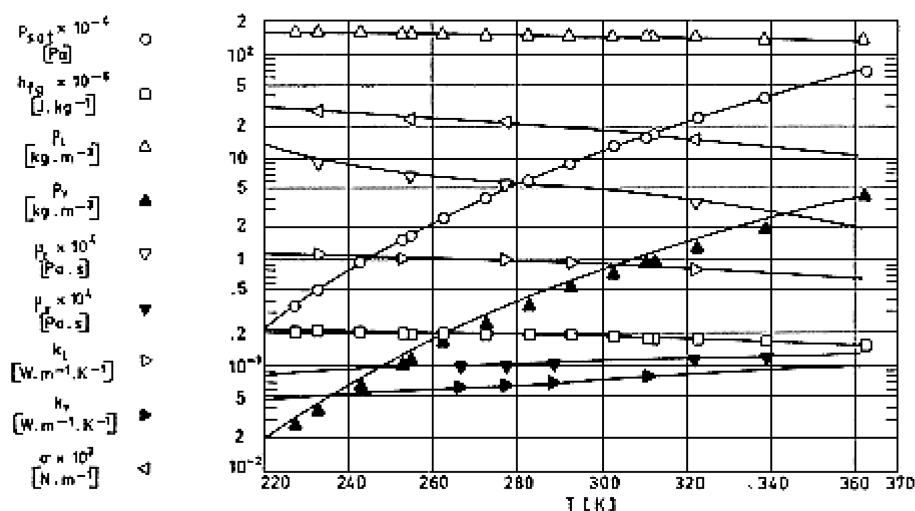
 $T_f = 162,1 \text{ K}$ $\rho_b = 1479 \text{ kg.m}^{-3}$ 

Figure 6-3: Relevant physical properties of Freon 11 as a function of temperature, T .
The labels correspond to experimental points. The expressions used to calculate the tabulated values are given below. Calculated by the compiler.

Formulae Used for Calculating the Values of the Physical Properties.

$$\log \frac{p_{sat}}{p_c} = -\frac{1,4825}{T/T_c} \left[1 - \left(\frac{T}{T_c} \right)^2 + 0,4701 \left(1 - \frac{T}{T_c} \right)^3 \left(3 + \frac{T}{T_c} \right) \right]$$

$$h_{fg} = 2,6414 \times 10^5 \left(1 - \frac{T}{T_c} \right)^{0,3744}, \quad 162 < T < 471$$

$$\rho_l = 1110 - \rho_v + 992,60 \left(1 - \frac{T}{T_c} \right)$$

$$\left[p + \frac{1430 \rho_v^2}{T^{0,5} (1 + 0,000468 \rho_v)} \right] (1 - 0,000468 \rho_v) = 60,52 T \rho_v$$

$$\mu_l = 10^{-4} \exp \left[-33,078 + \frac{26598}{T} - \frac{6,8953 \times 10^6}{T^2} + \frac{6,0975 \times 10^8}{T^3} \right], \quad 233 < T < 322$$

$$\mu_v = \frac{8,1254 \times 10^{-7} T^{3/2}}{92 + T}, \quad 266 < T < 338$$

[6-26]

$$k_l = 0,110 \left[1 - 2,6719 \times 10^{-3} (T - 233,2) - 4,1589 \times 10^{-6} (T - 233,2)^2 \right], \quad 233 < T < 322$$

$$k_v = 1,4346 \times 10^{-2} \left(\frac{T}{T_c} \right)^{1,47522}, \quad 266 < T < 310$$

Note: non-si units are used in this figure

$$\sigma = 0,0628 \left(1 - \frac{T}{T_c} \right)^{1,2299}, \quad 233 < T < 471 \quad [6-27]$$

Note: non-si units are used in this figure

Sources of Data.

VARIABLE	REFERENCES
p_{sat}	Raznjevic (1970) [69]. Scollon & Carpitella (1970) [83].
h_{fg}	
ρ_l	
ρ_v	
μ_l	Scollon & Carpitella (1970) [83].
μ_v	
k_l	Norris et al (1970) [64]; Scollon & Carpitella (1970) [83].
k_v	Scollon & Carpitella (1970) [83].
σ	

FLUID: METHANOL

$T_b = 337,5 \text{ K}$

$p_c = 9,709 \times 10^6 \text{ Pa}$

CHEMICAL SYMBOL: CH_3O

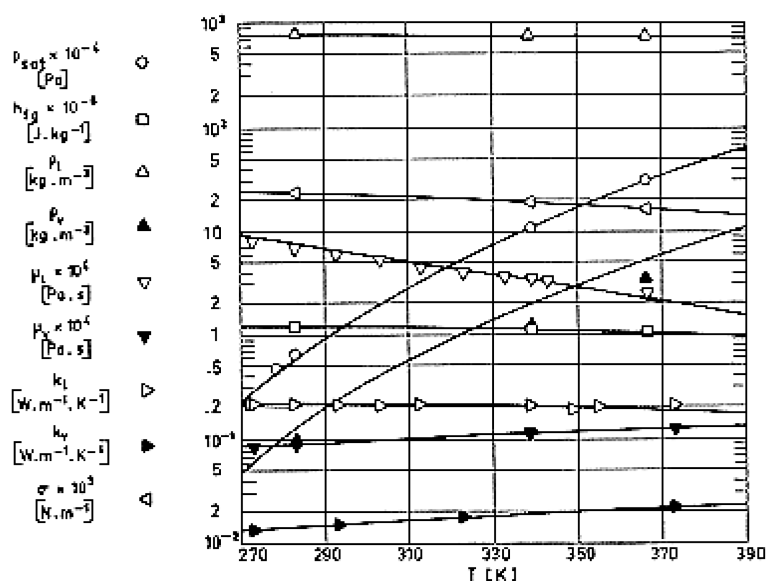
$T_c = 513,2 \text{ K}$

$\rho_c = 358 \text{ kg.m}^{-3}$

MOLAR MASS: 32,04

$T_f = 175,2 \text{ K}$

$\rho_b = 753,9 \text{ kg.m}^{-3}$



Note: non-si units are used in this figure

Figure 6-4: Formulae Used for Calculating the Values of the Physical Properties.

$$\log \frac{p_{sat}}{p_c} = -\frac{1,8132}{T/T_c} \left[1 - \left(\frac{T}{T_c} \right)^2 + 1,6960 \left(1 - \frac{T}{T_c} \right)^3 \left(3 + \frac{T}{T_c} \right) \right] \quad [6-28]$$

Note: non-si units are used in this figure

$$h_{fg} = 1,6028 \times 10^6 \left(1 - \frac{T}{T_c} \right)^{0,3623}, \quad 283 < T < 513 \quad [6-29]$$

Note: non-si units are used in this figure

$$\rho_l = 716 - \rho_v + 110,82 \left(1 - \frac{T}{T_c} \right) \quad [6-30]$$

Note: non-si units are used in this figure

$$\left[p + \frac{10807 \rho_v^2}{T^{0,5} (1 + 0,000726 \rho_v)} \right] (1 - 0,000726 \rho_v) = 259,50 T \rho_v \quad [6-31]$$

Note: non-si units are used in this figure

$$\mu_l = 10^{-4} \exp \left[-14,917 + \frac{10840}{T} - \frac{2,3992 \times 10^6}{T^2} + \frac{1,9493 \times 10^8}{T^3} \right], \quad 173 < T < 422 \quad [6-32]$$

$$\mu_v = \frac{1,1961 \times 10^{-6} T^{3/2}}{329 + T}, \quad 273 < T < 473$$

$$k_l = 0,213 \left[1 - 5,2339 \times 10^{-4} (T - 272) - 1,6473 \times 10^{-5} (T - 272)^2 \right] , \quad 272 < T < 373$$

Note: non-si units are used in this figure

$$k_v = 3,4511 \times 10^{-2} \left(\frac{T}{T_c} \right)^{1,4068} , \quad 273 < T < 373 \quad [6-33]$$

Note: non-si units are used in this figure

$$\sigma = 0,0453 \left(1 - \frac{T}{T_c} \right)^{0,8137} , \quad 283 < T < 513 \quad [6-34]$$

Note: non-si units are used in this figure

Sources of Data.

VARIABLE	REFERENCES
p_{sat}	Scollon & Carpitella (1970) [83].
h_{fg}	
ρ_l	
ρ_v	
μ_l	Raznjevic (1970) [69]; Scollon & Carpitella (1970) [83].
μ_v	
k_l	
k_v	
σ	Scollon & Carpitella (1970) [83].

FLUID: NITROGEN

$T_b = 77,35 \text{ K}$

$p_c = 3,393 \times 10^6 \text{ Pa}$

CHEMICAL SYMBOL: N_2

$T_c = 126,05 \text{ K}$

$\rho_c = 311 \text{ kg.m}^{-3}$

MOLAR MASS: 28,016

$T_f = 63,15 \text{ K}$

$\rho_b = 810 \text{ kg.m}^{-3}$

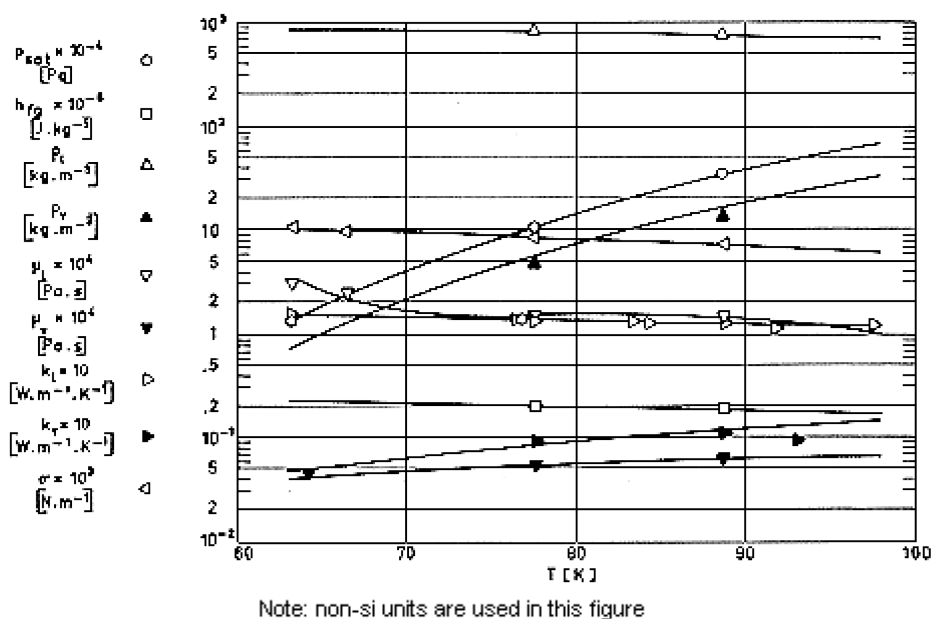


Figure 6-5: Relevant physical properties of Nitrogen as a function of temperature, T . The labels correspond to experimental points. The expressions used to calculate the tabulated values are given below. Calculated by the compiler.

Formulae Used for Calculating the Values of the Physical Properties.

$$\log \frac{p_{sat}}{p_c} = -\frac{1,3253}{T/T_c} \left[1 - \left(\frac{T}{T_c} \right)^2 + 0,3964 \left(1 - \frac{T}{T_c} \right)^3 \left(3 + \frac{T}{T_c} \right) \right] \quad [6-35]$$

Note: non-si units are used in this figure

$$h_{fg} = 0,2880 \times 10^6 \left(1 - \frac{T}{T_c} \right)^{0,3770}, \quad 63 < T < 126 \quad [6-36]$$

Note: non-si units are used in this figure

$$\rho_l = 622 - \rho_v + 466,60 \left(1 - \frac{T}{T_c} \right) \quad [6-37]$$

Note: non-si units are used in this figure

$$\left[p + \frac{1732 \rho_v^2}{T^{0,5} (1 + 0,00206 \rho_v)} \right] (1 - 0,00206 \rho_v) = 296,77 T \rho_v \quad [6-38]$$

$$\mu_l = 10^{-4} \exp \left[-50,109 + \frac{11988}{T} - \frac{9,4863 \times 10^5}{T^2} + \frac{2,5033 \times 10^7}{T^3} \right], \quad 63 < T < 110$$

$$\mu_v = \frac{1,5540 \times 10^{-6} T^{3/2}}{130 + T}, \quad 66 < T < 126$$

$$k_l = 0,158 \left[1 - 1,2470 \times 10^{-2} (T - 63,3) - 2,7138 \times 10^{-4} (T - 63,3)^2 - 4,2004 \times 10^{-6} (T - 63,3)^3 \right], \quad 63 < T < 110$$

Note: non-si units are used in this figure

$$k_v = 2,8865 \times 10^{-2} \left(\frac{T}{T_c} \right)^{2,5793}, \quad 77 < T < 122 \quad [6-39]$$

Note: non-si units are used in this figure

$$\sigma = 0,0154 \left(1 - \frac{T}{T_c} \right)^{0,6124}, \quad 63 < T < 126 \quad [6-40]$$

Note: non-si units are used in this figure

Sources of Data.

VARIABLE	REFERENCES
p_{sat}	Scollon & Carpitella (1970) [83].
h_{fg}	
ρ_l	
ρ_v	
μ_l	
μ_v	Raznjevic (1970) [69]; Scollon & Carpitella (1970) [83].
k_l	Scollon & Carpitella (1970) [83].
k_v	Raznjevic (1970) [69]; Scollon & Carpitella (1970) [83].
σ	Scollon & Carpitella (1970) [83].

FLUID: PROPANE

$T_b = 230,7 \text{ K}$

$p_c = 4,256 \times 10^6 \text{ Pa}$

CHEMICAL SYMBOL: C_3H_8

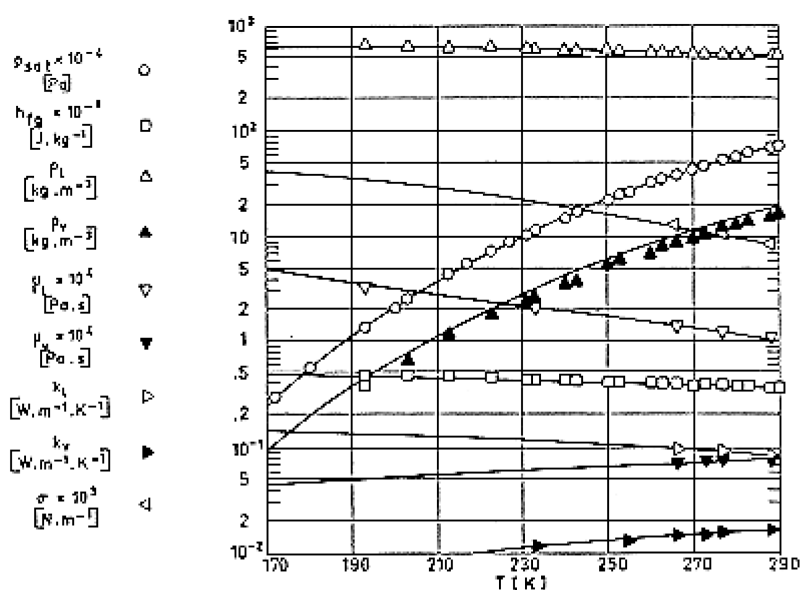
$T_c = 370 \text{ K}$

$\rho_c = 226 \text{ kg.m}^{-3}$

MOLAR MASS: 44,09

$T_f = 83,3 \text{ K}$

$\rho_b = 581,8 \text{ kg.m}^{-3}$



Note: non-si units are used in this figure

Figure 6-6: Relevant physical properties of Propane as a function of temperature, T , The labels correspond to experimental points. The expressions used to calculate the tabulated values are given below. Calculated by the compiler.

Formulae Used for Calculating the Values of the Physical Properties.

$$\log \frac{p_{sat}}{p_c} = -\frac{1,4473}{T/T_c} \left[1 - \left(\frac{T}{T_c} \right)^2 + 0,4535 \left(1 - \frac{T}{T_c} \right)^3 \left(3 + \frac{T}{T_c} \right) \right]$$

$$h_{fg} = 0,6422 \times 10^6 \left(1 - \frac{T}{T_c} \right)^{0,4023}, \quad 144 < T < 370$$

$$\rho_l = 452 - \rho_v + 344,64 \left(1 - \frac{T}{T_c} \right) \quad [6-41]$$

$$\left[p + \frac{7617 \rho_v^2}{T^{0,5} (1 + 0,00115 \rho_v)} \right] (1 - 0,00115 \rho_v) = 188,58 T \rho_v$$

Note: non-si units are used in this figure

$$\mu_l = 10^{-4} \exp \left[\frac{-4,9633 + \frac{2127,5}{T} - \frac{2,3239 \times 10^5}{T^2} + \frac{1,0312 \times 10^7}{T^3}}{1} \right], \quad 83 < T < 333 \quad [6-42]$$

Note: non-si units are used in this figure

$$\mu_v = \frac{9,5069 \times 10^{-7} T^{3/2}}{301 + T}, \quad 266 < T < 373 \quad [6-43]$$

Note: non-si units are used in this figure

$$k_l = 0,091 \left[1 - 4,9490 \times 10^{-3} (T - 266,5) \right], \quad 266 < T < 333 \quad [6-44]$$

Note: non-si units are used in this figure

$$k_v = 2,5703 \times 10^{-2} \left(\frac{T}{T_c} \right)^{1,7045}, \quad 233 < T < 373 \quad [6-45]$$

Note: non-si units are used in this figure

$$\sigma = 0,1265 \left(1 - \frac{T}{T_c} \right)^{1,7733}, \quad 266 < T < 370 \quad [6-46]$$

Note: non-si units are used in this figure

Sources of Data.

VARIABLE	REFERENCES
p_{sat}	Raznjevic (1970) [69]; Weast (1976) [95]; Scollon & Carpitella (1970) [83]; Das & Eubank (1973) [19].
h_{ig}	Raznjevic (1970) [69]; Scollon & Carpitella (1970) [83]; Das & Eubank (1973) [19].
ρ_l	
ρ_v	
μ_l	Reid & Serwood (1966) [70]; Scollon & Carpitella (1970) [83].
μ_v	Reid & Serwood (1966) [70]; Raznjevic (1970) [69]; Scollon & Carpitella (1970) [83].
k_l	Scollon & Carpitella (1970) [83].
k_v	Raznjevic (1970) [69]; Scollon & Carpitella (1970) [83].
σ	Scollon & Carpitella (1970) [83].

FLUID: WATER (Saturated)

$T_b = 373,2 \text{ K}$

$p_c = 2,212 \times 10^7 \text{ Pa}$

CHEMICAL SYMBOL: H_2O

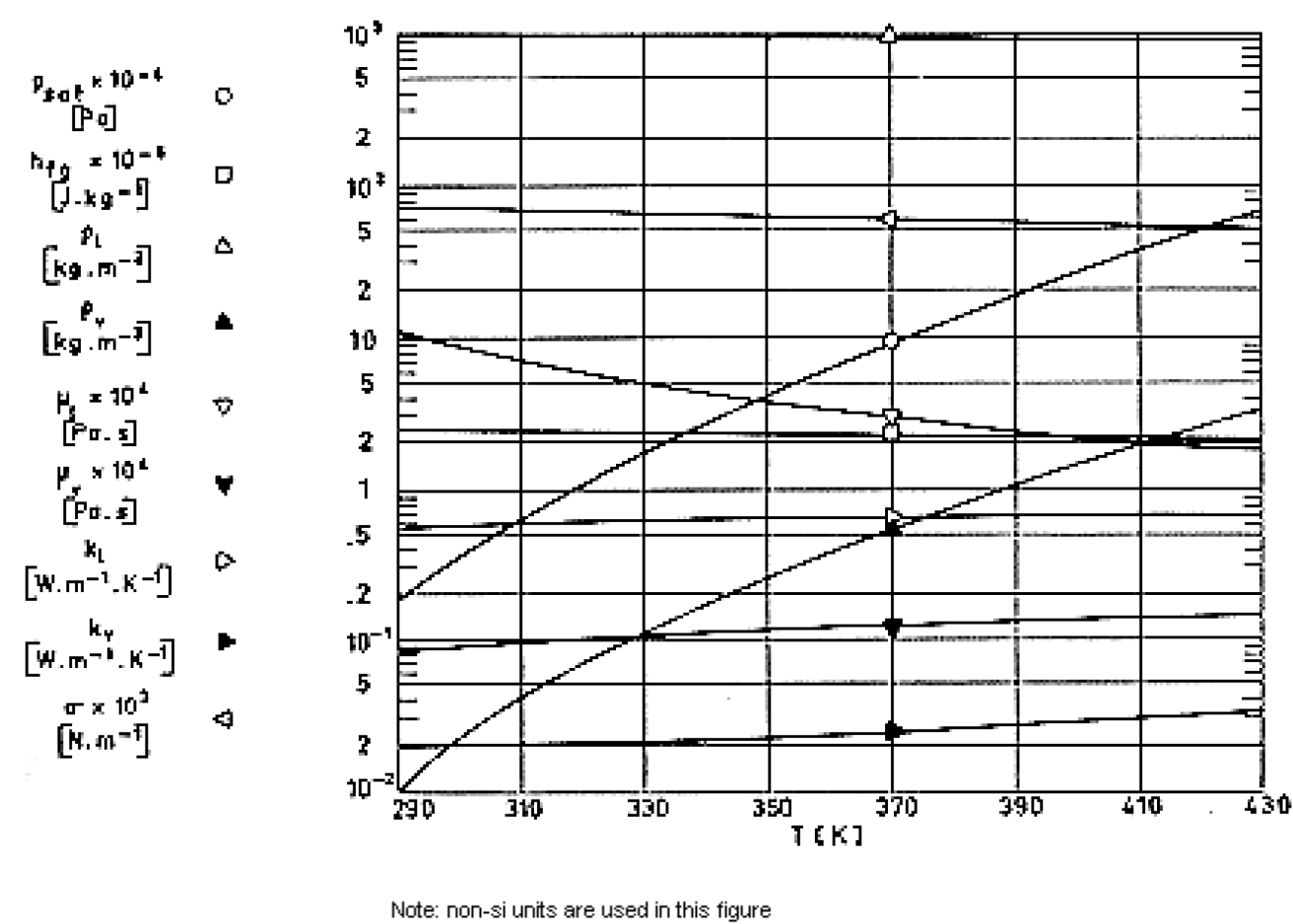
$T_c = 647,3 \text{ K}$

$\rho_c = 315,5 \text{ kg.m}^{-3}$

MOLAR MASS: 18,015

$T_f = 273,2 \text{ K}$

$\rho_b = 942,9 \text{ kg.m}^{-3}$



T [K]	Vapour pressure, $p_{sat} \times 10^{-4}$ [Pa]	Ht. Of Vapor., $h_g \times 10^{-6}$ [J.kg ⁻¹]	Density, ρ [kg.m ⁻³]		Viscosity, $\mu \times 10^4$ [Pa.s]		Thermal Conductivity, k [W.m ⁻¹ .K ⁻¹]		Surface Tension, $\sigma \times 10^3$ [N.m ⁻¹]	Figure of Merit, $N \times 10^{-9}$ [W.m ⁻²]
			Liquid	Vapor	Liquid	Vapor	Liquid	Vapor		
290	0,19	2,53	998,8	0,01	10,82	0,087	0,598	0,0192	73,25	171,1
300	0,36	2,44	996,6	0,03	8,53	0,091	0,613	0,0198	71,72	204,5
310	0,63	2,41	993,3	0,04	6,92	0,095	0,628	0,0204	70,13	242,6
320	1,06	2,39	989,4	0,07	5,74	0,099	0,640	0,0210	68,47	282,1
330	1,73	2,37	984,6	0,11	4,86	0,103	0,651	0,0217	66,74	323,1
340	2,73	2,34	979,3	0,18	4,18	0,107	0,659	0,0223	65,00	356,3
350	4,19	2,32	973,5	0,26	3,65	0,111	0,668	0,0230	63,15	390,8
360	6,25	2,29	967,1	0,38	3,23	0,115	0,674	0,0237	61,30	420,3
370	9,09	2,26	960,2	0,54	2,88	0,119	0,680	0,0246	59,42	447,7
380	12,94	2,24	952,9	0,75	2,60	0,123	0,683	0,0256	57,54	472,4
390	18,04	2,21	945,3	1,03	2,37	0,127	0,686	0,0266	55,65	490,5
400	24,68	2,18	937,1	1,38	2,17	0,131	0,688	0,0278	53,77	506,2
410	33,17	2,15	928,5	1,82	2,00	0,135	0,688	0,0291	51,90	518,0
420	43,89	2,12	919,5	2,36	1,85	0,139	0,687	0,0304	50,07	527,6
430	57,23	2,09	910,2	3,03	1,73	0,143	0,685	0,0319	48,27	530,8