Industrial Refrigeration

There is a tendency in our complex (and complexed) time, to discount simplicity. People sometimes feel that a simple, straightforward solution to a problem, or a simple, understandable down-to-earth answer to a question must be rejected. Their basis for this surprising view appears to be that such a simple solution somehow reduces the magnitude of their problem, and by reflection, tends to minimise their own personal importance.

Brinsley Le Poer Trench
Temple of the Stars

Industrial Refrigeration

Principles, Design and Applications

P. C. Koelet

with T. B. Gray

M
MACMILLAN

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Preface

Refrigeration is an exciting application of science and technology. It involves a range of subjects such as thermodynamics, mechanics, electrical technology, civil engineering, hydraulics, aerodynamics, chemistry and, last but not least, food technology. However, it must never be forgotten that refrigeration is not an end in itself but the means to an end – in most cases, to help condition man's environment and satisfy many of his nutritional needs. During the past 100 years, refrigeration has become indispensable to our society. Modern food processing, storage and transportation, for instance, would be impossible without the help of refrigeration.

I am convinced that all over the world engineers and technicians would like to learn more about the subject, and for this reason I have written this book in English. It is intended for those who, either as contractors or consultants, are involved in the design of refrigeration plants, and for those who are responsible for the purchasing or maintenance of these plants.

Industrial applications are generally larger than commercial applications and normally require a qualified operator on duty. Industrial refrigeration plants are found in the food processing, plastic, metallurgical and chemical industries, and on board ship. Such systems are based on a centralized design and normally use open-type compressors with high efficiency, long lifetime and power consumption above 30 kW.

This book deals not only with the installation and its components, but also with the products that are processed or stored in the refrigeration installation; it also considers the building in which the system operates.

The first chapters contain some useful and relevant thermodynamic background information. Later, a description of refrigeration and freezing systems is provided, as well as the calculation methods necessary to determine the refrigeration capacity and selection of the different components for the plant. This book is also about the application of refrigeration and therefore provides the reader with background information about the

composition of and the optimum storage conditions for food products. Finally, it deals with the economic aspects, maintenance procedures, fault finding and repair.

Teachers and students in universities, polytechnics and technical colleges or others who would simply like to study refrigeration should find this book very useful.

I wish to thank everyone who was helpful in creating this book, especially my wife Mrs Maria Teresa Koelet-Paranhos de Oliveira for the extensive and difficult word processing and also Mrs Ilonka Perl-Chatterjee who, together with my wife, spent many hours editing the text.

I should also like to express my grateful thanks to Tom Gray for his painstaking work in helping to produce the final draft; his constructive comments have made a significant contribution throughout. Nonetheless, I remain ultimately responsible for any errors that may remain.

Last but not least I would like to acknowledge the assistance of all the individuals and companies quoted in the References at the end of the book.

PIETER C. KOELET

Meise, Belgium, 1991

Symbols and Units

Symbols

A	m^2	Surface
a	m^2/s	Temperature conductivity coefficient
c, c_p, c_v	$\text{kJ}/(\text{kg K})$	Specific heat
D	m^2/s	Diffusion coefficient
E	kJ	Energy
$\dot{E}$	$\text{kJ/s} (= \text{kW})$	Energy flow
F		Force
H	kJ	Enthalpy
h	kJ/kg	Specific enthalpy
J	$\text{g}/\text{m}^2/\text{m/s}$	Water vapour diffusion coefficient
k		Isentropic exponent
k	$\text{W}/(\text{m}^2 \text{K})$	Heat transmission coefficient
L	kJ/kg	Specific evaporation enthalpy
l	kJ/kg	Specific melting enthalpy
M	kJ/kmol	Relative molecular mass
m	kg	Mass
$\dot{m}$	kg/s	Mass flow
n		Exponent of polytrop
n	$1/\text{s}; 1/\text{min}$	Rotation number
n	kmol	Molecular quantity
P	kW	Power
p	$\text{Pa} = \text{N}/\text{m}^2; \text{bar}$	Pressure
Q	kJ	Heat load
Q_o	kW	Refrigeration flow
$\dot{Q}_o$	$\text{kJ/s} (= \text{kW})$	Heat flow
q	kJ/kg	Specific heat load
q_o	kJ/kg	Specific refrigerating load
q_o, v	kJ/m^3	Volumetric refrigerant load

R kJ/(kg K)	Gas constant
R kJ/(kmol K)	Universal or absolute gas constant
S kJ/K	Entropy
s kJ/(kg K)	Specific entropy
T K	Absolute temperature
T_c K	Condensation temperature
T_e K	Evaporation temperature
T_o K	Room temperature
T_p K	Product temperature
t °C	Temperature
t h	Time
U m/s	Velocity
U kJ	Internal energy
V m ³	Volume
V' m ³ /s; m ³ /h	Volume flow
ν m ³ /kg	Specific volume
W kJ; kW h	Work
α W/(m ² K)	Heat-transfer coefficient
β kg/(Pa/m ² /s)	Matter transfer coefficient
δ m	Thickness
ϵ kg/kg; %	Mass proportion
ϵ_0	Cold factor
η	Efficiency coefficient
η Pa s = N s/m ²	Dynamic viscosity
λ	Filling ratio
λ W/(m K)	Thermal conductivity coefficient
ν m ² /s	Kinematic viscosity
π	Pressure ratio
ρ kg/m ³	Density

International Units

The unit in which heat was expressed in the past was the calorie. 1 kcal of heat was the quantity necessary to raise the temperature of 1 kg of water by 1 degree. This unit was used until the 1970s in continental Europe. Often the British Thermal Unit (Btu) was used in English-speaking countries, and ‘tons of refrigeration’ in the USA. There is now an internationally agreed system of units called the SI (*Système International*). In this system a quantity of heat is expressed in joules (1 calorie = 4.1868 joules). The capacity of an installation is no longer expressed in calories/h, or in Btu, but in kW. The International System defines the unit of temperature as the kelvin, rather than °C or °F (1°C is equivalent to 1 kelvin, 0°C is 273.15 kelvin).

The SI or International System is based on six basic units plus two supplementary units. These are:

Unit of length	= metre (symbol m)
Unit of mass	= kilogram (symbol kg)
Unit of time	= second (symbol s)
Unit of electric current	= ampere (symbol A)
Unit of temperature	= kelvin (symbol K)
Unit of luminous intensity	= candela (symbol cd)
Unit of plane angle	= radian (symbol rad)
Unit of solid angle	= steradian (symbol sr)

The system uses the same units for energy, no matter what kind of energy is being considered. 150 years ago Newton propounded his laws of motion: his ‘second law’ is often expressed by force is equal to mass multiplied by acceleration, or $F = m \times a$. In honour of his achievement

the new unit of force is called the newton (symbol N). It is the force required to accelerate a body of 1 kg mass at 1 m/s^2 . Previously, the unit of force was the pound or the kg:

1 kg is the force that a body of 1 kg weight is subjected to by the pull of gravity at a certain point in Paris

$$1 \text{ kg force} = \text{kg mass} \times 9.807/\text{s}^2 = 9.807 \text{ N}$$

The old system was confusing in as much as force and mass were both expressed in kg. Also in an age of space exploration, units based on gravitational force at a certain point of a certain planet are not logical.

Pressure = force/ m^2 . The unit of pressure is now 1 N/m^2 , also called 1 Pascal (1 Pa). As this unit is small, for liquids and gases we use the unit $1 \text{ bar} = 10^5 \text{ Pa} = 10^5 \text{ N/m}^2$. 1 kg/cm^2 in the old metric system = $9.807 \times 10^4 \text{ N/m}^2 = 0.9807 \times 10^5 \text{ Pa}$.

The unit of energy is derived from work = force $\times$ distance. Thus the unit of energy is $1 \text{ N} \times 1 \text{ m} = 1 \text{ N m}$. This unit is now called 1 joule (1 J). 1 joule is the work done by a force of 1 N when it moves 1 m in the direction of the force. The old 1 kg (force) = 9.807 N.

$$1 \text{ kg m} = 1 \text{ m} \times (1 \text{ kg force} \times 9.807 \text{ N/kg force})$$

$$1 \text{ kg m} = 9.807 \text{ N m} = 9.807 \text{ J}$$

1 kcal was 427 kg m, which is $427 \times 9.807 \text{ J}$ or 4,187 J. Related to time, the old system used the unit of kcal/h. In the SI system, the unit of effort is the energy required to do work of $1 \text{ N m} = 1 \text{ J}$ in 1 second. The J/s is however called the watt (symbol W). We think J/s but say 'W'.

$$1 \text{ kcal/h} = \frac{4187}{3600} \text{ J/s} = 1.163 \text{ J/s or } 1.163 \text{ W}$$

$$1 \text{ kcal/kg} = 4187 \text{ J/kg} = 4.187 \text{ kJ/kg}$$

Specific heat is now expressed in J/(kg K). Remember also that it is no longer permissible to use the metric unit of horse power (HP) but rather W or kW (1 HP was 75 kg m or 0.736 kW).

$$\text{Kinematic viscosity } \nu: 1 \text{ centistoke} = 1 \text{ m m}^2/\text{s}$$

$$\text{Dynamic viscosity } \eta: 1 \text{ centipoise} = 1 \text{ m Pa s}$$

Speeds of revolution are no longer expressed as revolutions per minute (rpm):

$$1 \text{ rpm} = \pi/30 \text{ rad/s}$$

$$1 \text{ rad/s} = 30/\pi \text{ rpm}$$

Notwithstanding this, however, rpm are still used in this book. Experience has shown that few people in refrigeration technology use the new unit. In general, however, new units are being used routinely in many countries by refrigeration engineers.