ENERGY
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Waste heat recovery

Energy, Mines and
Resources Canada

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PREFACE

Much has been learned about the art and science of managing energy during the past decade. Today, energy management is a seriously applied discipline within the management process of most successful companies.

Initially, in the early 1970's, energy conservation programs were established to alleviate threatened shortages and Canada's dependency on off-shore oil supplies. However, dramatic price increases quickly added a new meaning to the term "energy conservation" — reduce energy costs!

Many industrial, commercial and institutional organizations met the challenge and reduced energy costs by up to 50%. Improved energy use efficiency was achieved by such steps as employee awareness programs, improved maintenance procedures, by simply eliminating waste, as well as by undertaking projects to upgrade or improve facilities and equipment.

In order to obtain additional energy savings at this juncture, a greater knowledge and understanding of technical theory and its application is required in addition to energy efficiency equipment itself.

At the request of the Canadian Industry Program for Energy Conservation, the Commercial and Institutional Task Force Program and related trade associations, the Industrial Energy Division of the Department of Energy, Mines and Resources Canada has prepared a series of energy management and technical manuals.

The purpose of these manuals is to help managers and operating personnel recognize energy management opportunities within their organizations. They provide the practitioner with mathematical equations, general information on proven techniques and technology, together with examples of how to save energy.

For further information concerning the manuals listed below or material used at seminars/workshops including actual case studies, please write to:

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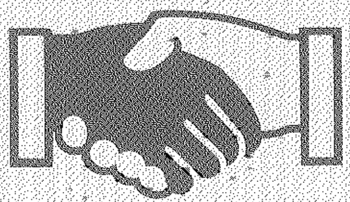
INTRODUCTION



Waste heat can be interpreted as heat rejected from a facility to the environment. Recovery and reuse of this heat has the potential for reducing energy costs and improving profitability of Canadian businesses. Although energy cost escalation rates have slowed in the last few years, a need to reduce energy consumption persists. This manual presents a systematic approach to defining and implementing waste heat recovery projects for Industrial, Commercial and Institutional facilities.

Purpose

The following summarizes the purpose of this manual:

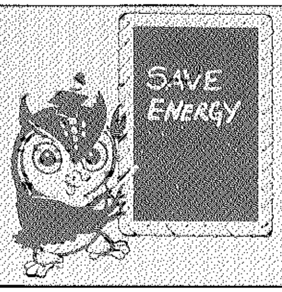
- to introduce the fundamental principles associated with heat transfer, waste heat availability, and waste heat recovery and reuse.
- to identify potential recoverable waste heat sources and applicable areas of utilization.
- to discuss equipment systems and techniques available for waste heat recovery.
- to present case studies and examples of waste heat recovery.

Contents

The contents of this manual have been subdivided into the following sections:

- "Fundamentals" discusses waste heat recovery including concepts required to identify waste heat available, heat exchange and heat pumping, principles of operation, conducting waste heat recovery audits, mass/energy balances, waste heat energy cascading and upgrading.
- "Sources and Applications" addresses sources of waste heat and gives practical suggestions for waste heat recovery applications.
- "Equipment/Systems" describes the theory, equipment and applications of the various recovery systems.
- "Energy Management Opportunities" presents several worked examples of waste heat recovery projects so as to provide insight into heat recovery applications.
- "Appendices" include tables, a glossary of terms, and conversion factor tables.

FUNDAMENTALS



Introduction

The reduction or reuse of waste heat provides an excellent opportunity for cost saving within Industrial, Commercial and Institutional facilities in Canada. This section of the manual is intended to provide/refresh the reader with the basic terms and tools necessary to quantify potential opportunities and to provide some background about the equipment available to reduce/recover waste heat.

Fundamental Heat Energy Principles

Heat and Heat Transfer

Experience shows that when a hot object is brought into contact with a cold object, the hot object becomes cooler and the cold object becomes warmer. This energy in transit is a result of a temperature difference and is called ''heat''. The fact that heat always flows from a higher to a lower temperature leads to the concept that temperature is the driving force for the transfer of energy as heat.

''Heat transfer'' deals with the mechanism(s) responsible for transferring heat from one place to another when a temperature difference exists between two objects.

Heat is measured in kilojoules (kJ) of energy and heat transferred is usually expressed as a unit of time, i.e., kJ/s or kJ/h.

Quality and Availability

The ''quality'' of heat energy can be described as its capability to cause change. In terms of waste heat, it is the quantity of useful energy available out of the total heat energy contained in a waste heat source.

''Availability'' is another term used to describe the nature of an energy source. The higher the quality of an energy source, the more available is its energy for use.

For a heat source, temperature is the measure of its quality and availability. The higher the temperature of a substance, the greater the amount of heat energy that can be extracted from it. Most industrial processes and commercial uses lower the temperature of the heat energy by putting it to use, thereby ''degrading'' the quality of heat.

Waste Heat

Waste heat can be defined as the heat contained in a substance rejected from a process at a temperature higher than the ambient levels of the plant. More fully, waste heat is any source of rejected heat having a portion which may be recovered and re-used economically. As will be discussed later, sources of waste heat may include gases, solids and liquids.

Cascading

Energy cascading can be defined as the organization of the flow and reuse of energy through various systems, production processes and equipment, to achieve the maximum efficiency of energy use. In essence, the objective is to use the maximum amount of energy available from a given source. The maximum efficiency is obtained through a sequential degradation or lowering of the quality of energy as each task is performed, in the same sense as the potential energy of falling water diminishes in the rapids and waterfalls of a river. It is this comparison which has led to the adoption of the word cascading to describe the concept.

Economics and practicality are crucial factors which limit the degree of cascading that can be achieved in a system. In most situations energy cascading can be optimized by retrofit measures which extract waste heat from higher temperature operations to perform relatively lower temperature tasks. An example is the generation of hot water in an apartment building using boiler exhaust gases as an energy source instead of generation by direct combustion of fuel.

Heat Content of Substances

Certain calculations are required to determine the heat content of waste heat sources and hence a variety of equations are presented below for the use of the reader. As will be seen, the applicability of any particular equation may depend on the material itself as well as the state of the material.

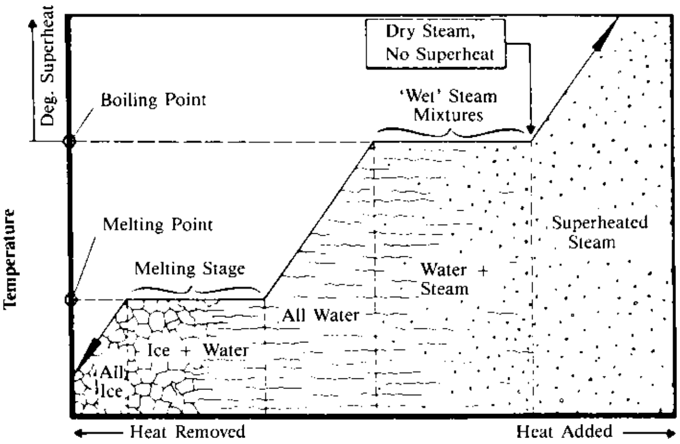
Sensible and Latent Heat

When heat energy is added to, or removed from a substance, either the temperature of the substance changes or the substance changes state.

Heat energy associated with a change in temperature is called sensible heat. The amount of energy is dependant upon the temperature change, the amount of material, and the specific heat of the material expressed in kJ/(kg·°C).

Heat energy associated with a change of state (or phase) is called latent heat. Figure 1 illustrates the change of state process for ice-water-steam. When the change of state is from steam to water, the latent heat of condensation is removed. When the change of state is from water to steam, the latent heat of evaporation is added. For a given material, the latent heat of evaporation is equal to that of condensation at a given temperature and pressure.

Latent heat is generally dependent on material properties, temperature and pressure. The units for latent heat are expressed in kJ/kg.



Example of Change of State
Figure 1

Enthalpy

The quantity of heat energy in a substance depends upon its heat capacity, the temperature change it experiences and whether or not it goes through a change of phase. This energy content can be expressed quantitatively by the use of a term known as heat content or "enthalpy", commonly denoted as "h" (kJ/kg). For ease of calculations, it is assumed that the enthalpy of all substances in a system is zero at a base temperature. For example, this base temperature is 0°C for steam tables. For most refrigerant tables, -40°C is the base temperature.

Enthalpy is a property of state of a substance; that is, for a given material its value is always the same at a given temperature and pressure. Change in enthalpy can be calculated as follows:

$$Dh = h_{final} - h_{initial}$$

- The enthalpy of water (h_f) is a measure of the amount of heat energy contained in the water (sensible heat) at a specific temperature.
- The enthalpy of evaporation (h_{fg}) (correctly called the latent heat of vaporization) is the quantity of heat energy required to convert one kg of water to one kg of steam at the given pressure.
- The enthalpy of steam (h_g) is the total energy contained in dry saturated steam at the given pressure.

This quantity of energy is the sum of the enthalpy of the liquid (h_f) and the amount of energy required to evaporate one kilogram of water for a specific temperature (h_{fg}) and can be expressed in the following equation:

$$h_g = h_f + h_{fg}$$

Where, h_g = Enthalpy of dry saturated steam (kJ/kg)

h_f = Enthalpy of water (kJ/kg)

h_{fg} = Enthalpy of evaporation (kJ/kg)

Table 1 in the Appendix presents the enthalpies for water and steam.

Calculation of Sensible Heat Transfer

The amount of sensible heat that is transferred to a substance can be determined by the following equation:

$$Q = M \times cp \times DT$$

Where, Q = amount of heat transferred (kJ/h)
M = mass of the substance (kg/h)
cp = Specific heat of the substance (kJ/kg·°C)
DT = Differential Temperature

"Specific heat", cp, of a material is the amount of heat absorbed per unit mass of a material for a unit temperature rise of the body and is expressed in kJ/kg·°C. A list of cp values for a variety of materials is presented in Table 2 in the Appendix.

Other expressions of flowrates can be used provided appropriate conversion factors are incorporated into the equation. For example, the sensible heat transferred for air may be approximated by the equation:

$$Qs = fa \times (T1 - T2) \times 4.345$$

Where, Qs = Sensible heat flow (kJ/h)
fa = Rate of air flow (L/s)
T1 = Warmer temperature (°C)
T2 = Cooler temperature (°C)
4.345 = a factor which accounts for the specific heat of dry air and conversion to common units.

The factor 4.345 would increase slightly for air containing water vapor, but this value is considered sufficiently accurate for estimating purposes.

Example: A facility discharges 10,000 L/h of process water at 70°C. If the water is cooled to 20°C, how much heat is potentially available for recovery?

$$Q = M \times cp \times DT$$

Mass of water = 10,000 L/h x 1kg/L
cp of water = 4.18 kJ/kg·°C (from Table 2)

$$DT = (70 - 20)^\circ C = 50^\circ C$$

The amount of heat available for recovery is therefore:

$$Q = 10{,}000\ kg/h \times 4.18\ kJ/kg\cdot^\circ C \times 50^\circ C = 2{,}090{,}000\ kJ/h$$

As can be seen by comparing the above two equations:

h_f = cp x DT

An alternative means of calculating the sensible heat available is to use the enthalpy equation. In this case:

Q = M x Dh_f

M = 10,000 kg

Dh_f = h_{final} - $h_{initial}$

h_{final} = 292.97 kJ/kg (from Table 1)

$h_{initial}$ = 83.86 kJ/kg (from Table 1)

Q = 10,000 kg/h x (292.97 - 83.86) kJ/kg

= 2,091,100 kJ/h

Note: The difference in the heat required as determined by the two methods is a result of rounding in the value of cp for water.

Calculation of Latent Heat Transfer

The amount of heat transfer required to evaporate (or condense) a liquid (or gas) can be calculated by the formula:

Q = M x h_{fg}

Where, Q = heat transferred (kJ/h)

M = mass of the substance (kg/h)

h_{fg} = latent heat of vaporization (kJ/kg).

Table 3 in the Appendix lists Heat of Vaporization for a variety of materials. As discussed previously, steam tables (Table 1) can be used to obtain latent heat of vaporization for water at a variety of conditions.

Example: Dry excess steam is discharged from a process at 100°C and atmospheric pressure. The quantity of steam discharged is 1,000 kg/h. The amount of latent heat available for recovery from this source on an hourly basis if the steam is all condensed to water can be calculated as follows:

Q = M x h_{fg}

M = 1,000 kg/h

h_{fg} = 2257 kJ/kg (from Table 1)

Q = 1,000 kg/h x 2257 kJ/kg

= 2,257,000 kJ/h

It should be noted that the condensate is generated at 100°C and offers further potential for energy recovery.

The latent heat exchange for air may be calculated by using a modified version of the above equation. Such an equation accounts for the humidity content of the air. The reader is referred to Manual 10 for a detailed description of calculating latent heat exchange for air.

Heat Transfer Mechanisms

Waste heat recovery systems involve transfer of heat. Understanding of the fundamentals of heat transfer mechanisms is therefore important to evaluating waste heat recovery benefits.

Transfer of heat occurs by three different mechanisms; radiation, conduction or convection. These mechanisms are described below.

Radiation

All hot bodies emit radiation in the form of heat, which can be received by another solid body in the path of heat radiation. The most common example of the radiative mode of heat transfer is the energy the earth receives from the sun.

For radiation heat transfer to be significant, temperature must be high. For instance, heat transfer by radiation only becomes significant for process furnaces at temperatures above 600°C. In most waste heat recovery applications the quantity of heat transferred by radiation is generally insignificant.

Conduction

Conduction is the process by which heat flows from a region of higher temperature to a region of lower temperature within a medium (solid, liquid or gaseous), or between different mediums in direct physical contact.

A typical example of heat conduction may be displayed by holding one end of a metal bar in a flame. Experience tells us that the heat will be conducted through the bar from the hot end to the cool end, causing the bar to become too hot to hold.

The observable effect of heat conduction is an equalization of temperature between the bodies in contact. However, if differences in temperature are maintained by the addition or removal of heat at different points, a continuous flow of heat will be established from the hotter to the cooler region.

Conduction is the only method of heat flow in solids. Conduction is also important in fluids but in non-solid mediums, it is usually combined with convection and in some cases with radiation.

Convection

''Convection'', heat transfer occurs when a moving gas or liquid comes into contact with a solid surface of a different temperature. Convection occurs in parallel to, and augments, heat transfer by conduction as the warmed (or cooled) fluid is swept away from the hot (or cold) solid surface and is replaced by fresh fluid. The greater the fluid velocity the faster is the heat transfer rate for a given temperature difference. Natural convection involves movement of the fluid over the heating surface through the heating effect only. A typical example is the heating of water in a tank in which a heating coil is immersed. In forced convection, a motive force such as a pump or fan is used to circulate the fluid.

Waste Heat Recovery Technologies

There are four general technologies used to recover waste heat. These include:

- Direct Usage
- Heat Exchangers
- Heat Pumps
- Vapour Recompression

The first two technologies involve using waste heat ''as is''. In such situations, the waste heat is of adequate quality for use elsewhere.

Waste heat is often available at a temperature lower than the potential load requirement. ''Waste heat upgrading'' refers to boosting the energy level of a waste heat stream so that it might perform more useful work than could otherwise be achieved. This can be accomplished through the use of heat pumps or by direct vapour compression where the waste heat is contained in vapours.

Direct Usage

Direct heat usage as the name implies involves using the waste heat discharge ''as is''. Typical examples might include:

- using boiler off gases for drying;
- using ''spent'' cooling water from a heat exchanger for hot water;
- using hot air from a mechanical room to heat a storage area;

In some cases only minimal alterations may be required to permit utilization of the waste heat discharge. However, special attention must be paid to the condition of the waste heat discharge especially in regards to potential contaminants such as harmful chemicals or unwanted moisture.

Heat Exchangers

Heat exchangers provide a means of transferring heat from one stream to another without the actual mixing of the two streams. The two streams may need to be separated for either of the following reasons:

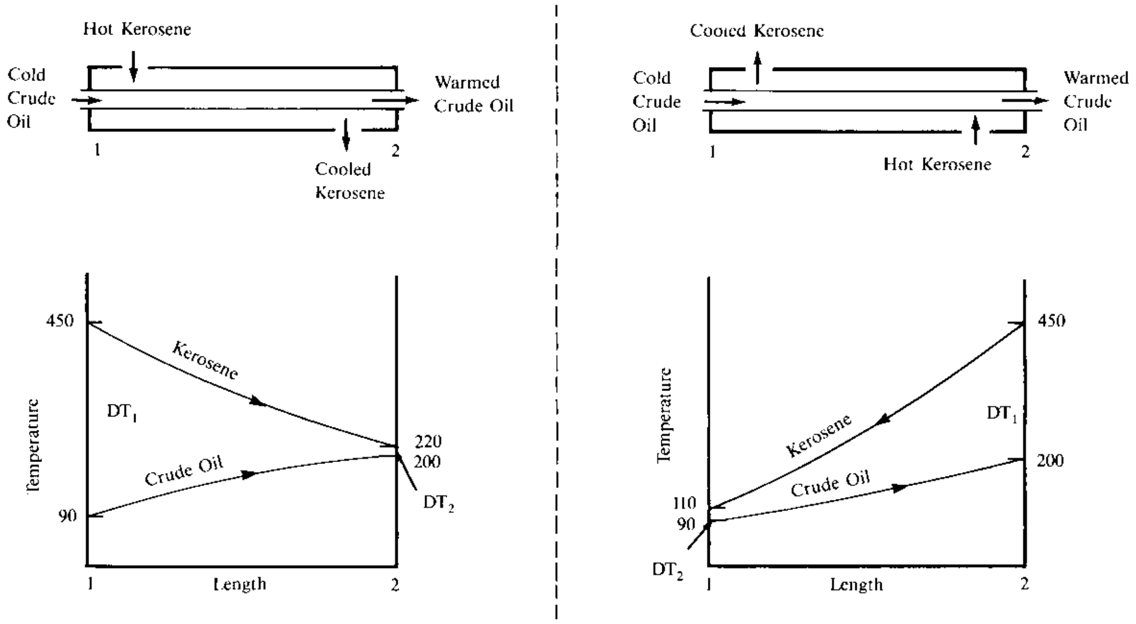
- to prevent one stream from contaminating the other (extremely important in food processing, especially in terms of avoiding contamination of potable water or the food product);
- to maintain a pressure difference that may exist between the two streams.

It may be necessary, in some situations, to use a third fluid. For example, an intermediate stream could be used to transport the waste heat over long distances when the source and demand are far apart.

In a heat exchanger the two fluids may flow:

- in opposite directions or "counterflow";
- in the same direction or "parallel flow";
- perpendicular to each other or "crossflow".

Figure 2 shows the first two of these configurations and illustrates the temperature profiles of the respective hot and cold fluids as they pass through a heat exchanger.



Parallel Flow
Heat Exchanger

Counter Flow
Heat Exchanger

Heat Exchanger Temperature Profiles

Figure 2

The equation for heat transfer in a heat exchanger is:

$$Q = U \times A \times (LMTD)$$

Where,
Q = rate of heat transfer (kJ/s)
U = overall heat transfer coefficient ($kJ/m^2 \cdot s \cdot {}^\circ C$)
A = heat transfer area (m^2)
LMTD = log mean temperature difference (°C)

Values for "U" have been determined for a variety of heat exchange applications. Table 4 in the Appendix is one such list of values for many common applications. For applications other than those listed published tables listing "U" values are available.

As seen in Figure 2, the temperature profiles for both hot and cold fluid along the exchanger length are not straight lines. Thus the temperature difference between the two streams cannot be calculated from an arithmetic average of inlet and outlet temperature differences.

In this situation, the "Log Mean Temperature Difference" is used and is an accurate representation of the actual conditions in an exchanger. It is calculated as follows:

$$\text{LMTD} = \frac{DT_1 - DT_2}{\ln\left(\dfrac{DT_1}{DT_2}\right)}$$

Where, DT_1 = temperatures difference between hot and cold fluids at one end of the heat exchanger.
DT_2 = temperature difference between hot and cold fluids at the other end of the heat exchanger.
ln = denotes natural logarithm operator.
Note: if $DT_1 = DT_2$ then $\text{LMTD} = DT_1 = DT_2$

For the example shown in Figure 2b the LMTD for a counterflow heat exchanger would be:

$$\text{where: } DT_1 = (450\text{-}200)°\text{C} = 250°\text{C}$$

$$DT_2 = (110\text{-}\ 90)°\text{C} = 20°\text{C}$$

$$\text{LMTD} = \frac{250 - 20}{\ln\left(\dfrac{250}{20}\right)}$$

$$= 91°\text{C}$$

Alternatively Figure 3 can be used to graphically determine LMTD.

For Expansion Of Scales, Multiply All Scales By 10

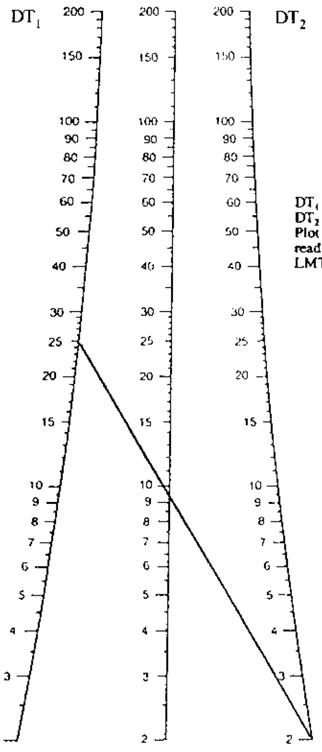


Figure 3

DT_1 = 250°C
DT_2 = 20°C
Plot as shown and draw a connecting line. LMTD can read where the line crosses middle scale.
LMTD = 91°C

In theory, it should be possible to heat 10 L/s of 20°C water to 25°C by using 10 L/s of 30°C warm water if perfect heat exchange was possible. However, in practical terms, this is not possible. Items such as inefficiencies in heat transfer rates owing to fouling, physical limitations of equipment size and heat loss to surroundings, require a more practical approach.

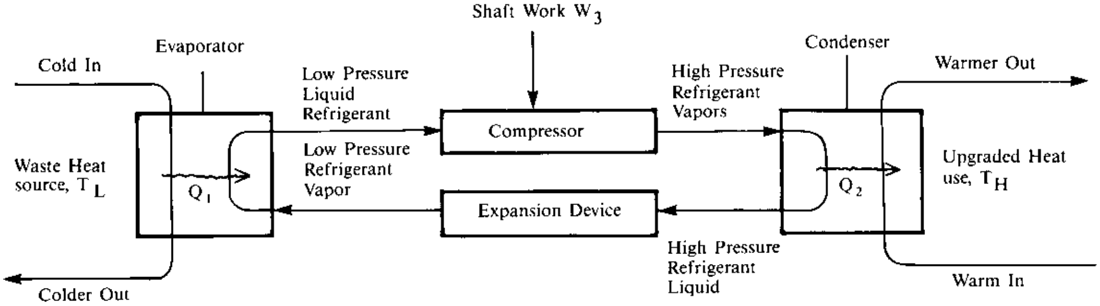
In normal practice, a reasonable "approach temperature" (the temperature difference between the cooling water and the fluid to be cooled) must be selected. For waste heat recovery applications an approach temperature of 5°C to 10°C is typical. For some process operations, it may be necessary to obtain approach temperatures of 2°C to 5°C. However, the smaller the approach temperature the larger the heat exchanger and hence the higher the cost.

Heat Pumps

Heat pumps provide a means of raising the temperature of waste heat to increase its usefulness. For example, a heat pump may be used to recover heat from a building exhaust stream, raise the temperature of this heat, and recycle it for heating the building.

The theory and definitions for heat pumps are discussed in Module 11, Refrigeration and Heat Pumps, and the reader is referred to that module for detail.

A basic heat pump system is shown in Figure 4. Low temperature waste heat is used to evaporate a liquid refrigerant under low pressure in the evaporator. The refrigerant vapour is then compressed to achieve an increase in its temperature due to the absorption of the mechanical energy of compression. The high temperature vapour passes through the condenser where its heat is released as it condenses to a liquid. The condensed fluid is then expanded to reduce its temperature and pressure before returning it to the evaporator.



Heat Pump Cycle
Figure 4

Heat pump performance is expressed by a term called "coefficient of performance", which is defined as:

$$COP = \frac{Q_H}{W}$$

Where, Q_H = total heat recovered in the condenser (kJ or W)

W = work input to the compressor (kJ or W).

The value of COP depends on the difference between the temperature at which the heat is delivered and the temperature at which the heat is extracted, that is, the degree of upgrading required. The larger this difference, the greater is the amount of work input, and smaller the COP.

In practical terms, a COP of, say 5, means that for every unit of energy used to operate the heat pump, 5 are returned.

Vapour Recompression

In cases where a waste heat stream is in the form of low temperature vapours, recompression is often a viable option. Vapour recompression involves compressing the waste stream vapour to increase its temperature and pressure in order to provide a useful source of energy. The compressed vapour is returned to the process for supplying the heat of evaporation. Thus the only energy input is power to the compressor. The coefficients of performance for vapour recompressors can be very high (5-10).

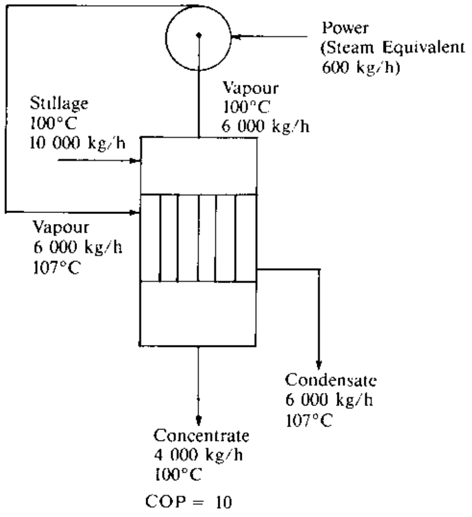
Vapour recompression can be achieved either mechanically or thermally.

- Mechanical Recompression:

  Mechanical vapour recompression is generally accomplished through the use of centrifugal and positive displacement compressors. Normally, compressed vapours are recycled back for use by the process which generates low pressure vapours. A typical application is in evaporation.

  Coefficients of performance for these systems are very high (6-10), as a relatively small degree of energy upgrading is required.

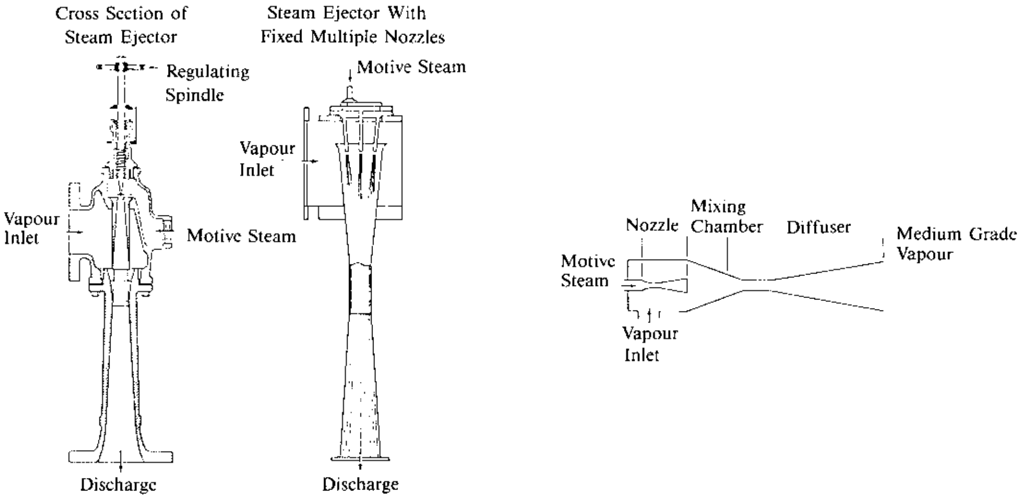
  The principle of mechanical vapour recompression is illustrated in Figure 5. Preheated feed enters the evaporator body at nearly its boiling point and the vapour is given off at 100°C. This vapour is compressed in a centrifugal blower and returned to the evaporator at a pressure of 129 kPa absolute corresponding to a saturation temperature of 107°C. This vapour can then give up its heat to the solution, generating more vapour. The feed, if not already available at its boiling point, as was in this example, can be preheated using the condensate and the concentrate.



Principle of Mechanical Vapour Compression Evaporation
Figure 5

- Thermal Recompression:

  Thermal vapour recompression is achieved by combining a low pressure vapour with a high pressure vapour to produce a medium pressure vapour. This process is accomplished through the use of steam ejectors. As shown in Figure 6, the total volume of upgraded vapour and its heat content is the sum of high and low grade vapour quantity and heat content.



Standard Types of Ejectors Used for Thermal Recompression
Figure 6

The coefficient of performance of a thermocompressor is equal to:

$$COP = \frac{Q_h}{Q_m}$$

Where, Q_h = heat delivered (kJ or W)

Q_m = sum of heat input from the motive vapour (kJ or W)

COP is high when:

- Motive steam pressure is high;
- Degree of required temperature increase is low.

Multi-Stage Operations

In many situations, a production process involving heating (or cooling) can be broken down into a number of steps in order to achieve an energy cascade. Such processes are referred to as multi-stage operations. Examples of conventional multi-stage operations include:

- Multi-Effect Evaporation
- Steam Flashing
- Other Multi-Stage Operations

Of the above, the latter is probably the most readily applicable for most situations. Basically, such multistage operations are an extension or practical application of the waste heat recovery technologies discussed in the proceeding pages. This is achieved by interconnecting process equipment through the use of heat exchangers, heat pumps, etc.

Multi-effect Evaporation and steam flashing are also multi-stage operations though somewhat limited in terms of applicability.

Energy Audit Methods

Energy Management Opportunities exist in systems used in Industrial, Commercial and Institutional facilities. The first step towards reducing fuel and electricity consumption is the performance of an energy audit. An energy audit traces the path of energy input, use and output, ultimately providing an indication of where potential energy cost savings may be realized. The energy cost saving measures may range from labour intensive projects to simple housekeeping and low cost measures. Many of these opportunities are recognizable during a walk through audit of the facility. The audit is usually more meaningful if a "fresh pair of eyes" generally familiar with energy management is involved. Typical energy saving items noted during a walk through audit are hot water heaters with unnecessarily high temperature set points, and damaged insulation. Alert management and operating staff, and good maintenance procedures can reduce energy usage and save money.

Not all items noted in a walk through audit are as easy to analyze as those described.

A diagnostic audit mathematically establishes the potential reductions in energy use obtained from changes and calculates potential dollar savings. Simple payback calculations can be performed to establish the financial viability of the opportunity once the estimated cost of the changes is established.

Reference should be made to the manual "Conducting an Energy Audit", in this series, for further detailed information on energy auditing.

The implementation of Energy Management Opportunities can be divided into three categories.

- Housekeeping refers to an energy management action that is repeated on a regular basis and never less than once a year. An example of this could be the calibration of important instruments.
- Low cost refers to an energy management action that is done once and for which the cost is not considered great. An example of a low cost item would be the direct use of a waste heat stream.
- Retrofit refers to an energy management action that is done once and for which the cost is significant. An example would be the installation of an economizer for hot water heating.

It must be noted that the division between low cost and retrofit is normally a function of both the size and the type of the organization as well as its cash flow position.

POTENTIAL SOURCES AND APPLICATIONS OF WASTE HEAT

Introduction

Completion of an energy audit can often result in the identification of various waste heat sources in a facility. The reduction, or elimination of waste heat should be the first concern. Only after such measures have been carried out should waste heat recovery be considered.

The prime justification of any waste heat recovery project is that there must be a demand for that recovered heat. As part of the audit process, potential uses for the recovered heat should become evident. Matches between heat available and heat required can then be developed to define a range of recovery options. These options may involve the use of heat exchangers, heat pumps, multi-stage operations or steam flashing, to maximize use of available energy.

Figure 7 presents examples of waste heat sources and typical temperature ranges as well as suggestions of recovery applications.

Formulation of Waste Heat Recovery Projects

A number of factors can have an important bearing on the success of waste heat recovery projects. Consideration of these factors, can eliminate non-viable options at an early stage with a corresponding savings in time and money. Factors to be considered include:

- **Compatibility Between Source and Demand:** A good match in quantity and quality of heat is often the single most critical factor in successful waste heat recovery projects. Compatibility is also very much affected by the operating schedules of the equipment and system. In this context, attention to the need for storage is critical. Highest utilization factors, and therefore most acceptable paybacks, are generally achieved for waste heat recovery projects integrated within a system.

Examples are:

- Preheating of feedwater or combustion air with boiler exhaust gases, blowdown, condensate.
- Low pressure steam recovery from turbines.
- Preheat make-up air from exhaust air.

Thermal storage can be used to improve the compatibility between a source and demand when their operating schedules do not coincide. As the name implies, thermal storage involves the collection of heating (or cooling) energy for use at a later time. The reader is referred to Module 19, ''Thermal Storage'' for more details in this regard.

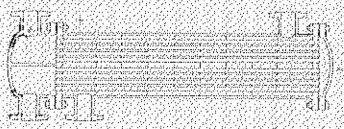
- **Accessibility:** The waste heat source should be easily accessible. By this it is meant the waste heat stream should be contained or as concentrated as possible. For example waste heat from flue gases are readily accessible since they are contained in chimney stacks or duct work. Waste heat contained in the air in a room is less accessible since more effort is required to contain and extract that heat.
- **Distance Between Source and Demand:** The shorter the distance between source and demand, the more viable a project is likely to be. The cost of an intermediate heat transfer system and heat losses from pipes and ducts are the key concerns and can adversely affect the viability of a waste heat recovery project.
- **Form and Condition of Waste Heat Source:** This is especially important in situations where heat exchange equipment is being considered. For instance, recovery of heat from gases is more expensive than from vapours and liquids because of low heat transfer coefficients. Presence of fouling and corrosive compounds further complicates recovery as heat exchanger erosion and corrosion must be considered.

Type of Facility	Waste Heat Source	Temperature (°C)	Recovery Applications
		High Grade	
Industrial	Electrical Refractory Furnace Exhaust	1600 - 2700	Process steam, preheat combustion air, space heating.
	Nickel Refining Furnace Exhaust	1375 - 1550	
	Fume Incinerator Exhaust	650 - 1550	
	Solid Waste Incinerator Exhaust	650 - 1000	
	Reheat Furnace Exhaust		
		Medium Grade	
Industrial	Gas Turbine Exhaust	375 - 550	Preheat combustion air, direct drying, space heating, heating process water, preheating boiler water.
	Diesel Generator Exhaust	375 - 500	
	Steam Boiler Exhaust	230 - 250	
Commercial	Drying and Baking Over Exhaust	230 - 600	Preheat combustion air, heating process water, preheat boiler water.
	Dryer Exhaust	150 - 230	
	Furnace Flue Gas	175 - 230	
		Low Grade	
Industrial	Steam Boiler Exhaust	150 - 230	Space heating, preheat combustion air, process heating.
	Dryer Exhaust	85 - 150	
	Process Steam Condensates	55 - 95	
	Condensate Tank Flash Steam		
	Waste Process Condensates		
	Hot Process Streams		
	Boiler Blow-Down		
	Diesel Generator Cooling Water		
Commercial	Steam Boiler Exhaust	85 - 1500	Space heating, preheat combustion air, process heating, temper ventilation air.
	Dryer Exhaust	150 - 230	
	Furnace Flue Gas		
Institutional	Steam Boiler Exhaust	150 - 230	Space heating, preheat combustion air, temper ventilation air, domestic water heating.
	Furnace Flue Gas	175 - 230	
		Very Low Grade	
Industrial	Cooling Water from Air Compressors	25 - 50	Space heating, direct (warm) water use, combustion air.
	Cooling Water from Power Plants	15 - 50	
	Warm Air from Ceiling Level	25 - 50	
	Process Wastewater Streams		
	Warm Product		
Commercial	Air Conditioning and Refrigeration Condenser Exhaust	30 - 45	Space heating, domestic water heating, temper ventilation air.
	Process Wastewater (laundry, etc.)	30 - 45	
Institutional	Air Conditioning and Refrigeration Condenser Exhaust	30 - 45	Space heating, domestic water heating, temper ventilation air.
	Kitchen Exhaust		
	Ventilation Exhaust		
	Vacuum Jet Ejector Exhaust		
	Fryer Exhaust		

Potential Sources and Applications of Waste Heat
Figure 7

- **Product Quality:** If heat is to be recovered from a product, the potential contamination of the product by the heat transfer fluid should be considered. This is of special concern in the food and beverage industries.
- **Degree of Upgrade Required:** When heat recovery from a source at temperatures lower than demand is desired, the extent to which the heat must be upgraded is an extremely important consideration. Capabilities of commercially available upgrading equipment need to be considered in determining the feasibility of heat upgrade projects.
- **Regulatory Aspects:** In some cases, special regulatory requirements such as those encountered in pharmaceutical and food processing industries, may affect the nature and type of recovery projects. For example, hot air from a potentially contaminated area may not be acceptable for direct heating of a food processing area.

EQUIPMENT SYSTEMS



Introduction

This section of the manual focuses on equipment available for the following waste heat recovery/utilization technologies:

- Direct Use
- Heat Exchange
- Heat Pumps
- Vapour Recompression

Direct use of waste heat requires no specialized pieces of equipment per se. Rerouting of piping, additional ductwork and/or possibly the installation of some type of thermal storage system is often all that is necessary. Through creative thinking and ingenuity it is possible to take advantage of the waste source and put it to use in a simple, cost effective manner.

Heat exchangers and heat pumps have the widest range of applicability, regardless of the industry type. Vapour Recompression can be used in some situations. However, it is generally limited to larger plants and complex processes.

This section of the manual concludes with a discussion of equipment used in multi-stage operations.

Heat Exchange Equipment

Heat exchangers are used for transferring energy from one stream to another unless the heat bearing stream can be used directly. Their use by industry is widespread and the technology is well established.

Heat exchangers are available in a number of designs and configurations to suit the varied needs, materials, temperatures and operating conditions and include the following:

- Shell and Tube
- Waste Heat Boilers
- Fin Tube
- Spiral
- Concentric Tube
- Plate
- Run-Around System
- Heat Wheels
- Heat Pipes

Figure 8 can be used as a general guide to selecting heat exchangers for waste heat recovery applications. However, each situation must be analyzed in detail to ensure that the most satisfactory selection is made. Expert advice on equipment selection and contact with suppliers regarding equipment availability can result in economies in time and cost and in trouble free operation.

Design characteristics, typical waste heat recovery applications and heat recovery efficiencies are discussed for the more common heat exchange units. Other configurations and applications do exist.

The heat recovery efficiencies are presented for guideline purposes only. Again, expert advice is necessary to fine tune flowrates, size of heat exchanger, etc.

It should be noted that high heat exchanger efficiencies are not always desirable nor necessary in waste heat recovery applications. Unless all of the heat in a waste heat stream can be utilized, recovery equipment with a lower efficiency may suffice to meet the job requirements. A less efficient device may also have other advantages such as larger passages (less pressure drop), easier maintenance, etc.

Specifications for Waste Recovery Unit **Commercial Heat Transfer Equipment**	Low Temperature from below 0°C - 120°C	Intermediate Temp. 120°C - 650°C	High Temperature Above 650°C	Recovers Moisture	Large Temperature Differentials Permitted	Packaged Units Available	Can Be Retrofit	No Cross-Contamination	Compact Size	Gas-to-gas Heat Exchanger	Gas-to-liquid Heat Exchanger	Liquid-to-liquid Heat Exchanger	Corrosive Gases Permitted With Special Construction
Shell-and-tube Exchanger	●	●			●	●	●	●	●		●	●	
Finned-tube Heat Exchanger	●	●			●	●	●	●	●		●		1
Waste Heat Boiler	●	●				●	●	●			●		
Spiral Heat Exchanger	●	●				●	●	●	●			●	
Concentric Tube Heat Exchanger	●	●			●	●	●	●	●		●	●	●
Concentric Tube Heat Exchanger Recuperator		●	●		●	2	●	●		●			●
Plate Heat Exchanger	●	●			●	●	●	●		●	●	●	●
Run-around System	●	●			●	●	●	●		●	●	●	
Heat Wheel Metallic	●	●		3		●	●	4	●	●			●
Heat Wheel Hydroscopic	●			●		●	●	4	●	●			
Heat Wheel Ceramic		●	●		●	●	●		●	●			●
Heat Pipe	●	●			5	●	●	●	●	●			●

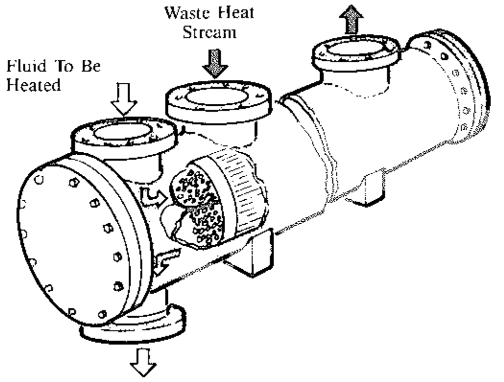
1. Can Be Constructed Of Corrosion-resistant Materials, But Consider Possible Extensive Damage To Equipment Caused By Leaks Or Tube Ruptures.
2. Off-the-shelf Items Available In Small Capacities Only.
3. Controversial Subject. Some Authorities Claim Moisture Recovery. Do Not Advise Depending On It.
4. With A Purge Section Added, Cross-contamination Can Be Limited To Less Than 1% By Mass.
5. Allowable Temperatures And Temperature Differential Limited By The Phase Equilibrium Properties Of The Internal Fluid.

Operation and Application Characteristics of Heat Exchangers
Figure 8

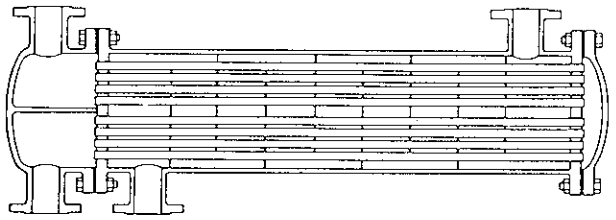
Shell and Tube Heat Exchanger

Shell and tube heat exchangers are the most widely used of all exchangers. They are relatively low cost compared to other types and are available in a tremendous range of sizes, capacities, materials of construction, etc. For these reasons, the shell and tube heat exchanger should be one of the first configurations evaluated in any potential waste heat recovery project.

A typical shell and tube exchanger is shown in Figure 9. This gas/liquid or liquid/liquid heat exchanger consists of a bundle of small, parallel tubes contained within a cylindrical shell. One fluid flows through the tubes and the other through the shell and over the tube bundle. Baffles are placed inside the shell as shown in Figure 10 to ensure that in each section the flow passes across the tubes flowing downward in the first, upward in the second section, and so on. Depending upon the header arrangements at the two ends of the heat exchanger, one or more tube passes can be achieved. For a two-tube pass arrangement, the inlet header is split so that the fluid flowing into the tubes passes through one-half of the tubes in one direction, then turns around and returns through the other half of the tubes to where it started, as shown in Figure 9. Two, four and six passes can be achieved by rearrangement of the header space.



Shell and Tube Heat Exchanger
Figure 9



Shell-and-Tube Heat Exchanger with Segmental Baffles: Two Tube Passes, One Shell Pass.
Figure 10

It is more expensive to design the shell for the higher pressure so the higher pressure fluid is circulated in the tubes while the lower pressure fluid flows through the shell. When a vapour contains the waste heat, it usually condenses, giving up its latent heat to the liquid being heated. In this application, the vapour is almost invariably contained within the shell. If the reverse is attempted, the condensation of vapours within small diameter parallel tubes causes flow instabilities.

Tube and shell heat exchangers are available in a wide variety of standard sizes with many combinations of materials for the tubes and shells. Figure 11 summarizes some of the attributes of two extremes in tube and shell exchangers which are available to illustrate the broad range of capacities that can be handled with these units.

SUMMARY OF RANGES OF SHELL AND TUBE SIZES AND CAPACITIES

Shell Diameter	Overall Length	Number of Passes Available	Flow Tubeside	Flow Shellside
100 mm	750 mm	2;4;6	7.5 to 115 L/s	55 to 250 L/s
760 mm	400 mm	2;4;6	950 to 12,000 L/s	750 to 7,300 L/s

Figure 11

Typical tube side design pressures for shell and tube exchangers are in the range of 860 to 1050 kPa. Maximum operating temperatures are typically 200°C. The pressure drop across the shell side is normally in the order of 3 to 30 kPa. In selecting units, it is desirable to keep tube side liquid velocities to less than 2.3 m/s. Reasons for this include:

- water flow at velocities of 2.3 m/s and above can become erosive resulting in rapid wear of the tubing.
- any small accumulation of scale in a unit that has been rated at high velocity causes a very sharp drop-off in heating capacity.
- the high pressure drop resulting from very high velocities can make pump selection difficult and costly.

Shell side velocities are normally less than 1.2 m/s.

Typical heat recovery efficiencies for these units are in the 60 to 80 percent range.

Shell and tube exchangers are generally difficult to clean and are not well suited for dirty applications. End plates, or heads can usually be removed to permit cleaning of tubes. A removable tube bundle makes the shell side easier to clean, although it adds to the cost and limits its use cycle.

Typical applications include heating liquids and/or gases by recovering heat from condensates from:

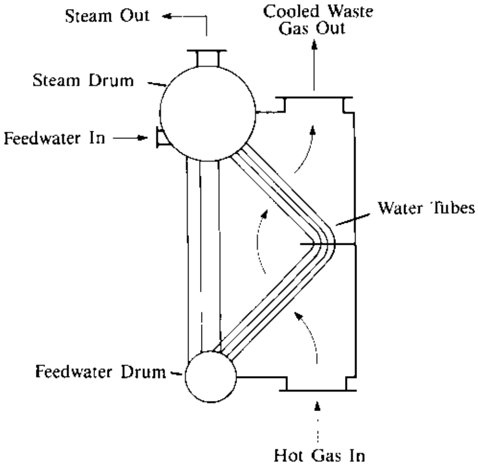
- refrigeration and air conditioning systems;
- process steam;
- furnace doors, grates, and pipe supports;
- engines, air compressors, bearings, and lubricants;
- distillation processes;
- boiler blowdown.

Waste Heat Boilers

Waste heat boilers based on shell and tube design are used to recover waste heat from high temperature exhausts in chimney stacks. Waste heat boilers are typically water tube boilers which use large volume, high temperature waste heat streams as a heat source as opposed to conventional fuel. Typical heat sources include hot exhaust gases from such equipment as gas turbines, incinerators, furnaces and reciprocating engines. Should the waste heat in exhaust gases be insufficient for generating the required amount of process steam, it is sometimes possible to add auxiliary burners. These systems burn fuel in the waste heat boiler or an afterburner may be added to the exhaust gas duct just ahead of the boiler.

Figure 12 indicates one arrangement that is used, where the exhaust gases pass over the water tubes twice before they are exhausted to the air. In order to conserve space, a more compact boiler can be produced if the water tubes are finned in order to increase the effective heat transfer area on the gas side. The diagram shows a feed water drum, a set of tubes over which the hot gases make a double pass, and a steam drum which collects the steam generated above the water surface.

Waste heat boilers are built in capacities from less than 500 to as high as 500,000 L/s of exhaust gas. Typical heat recovery efficiencies are 40 to 50 percent.



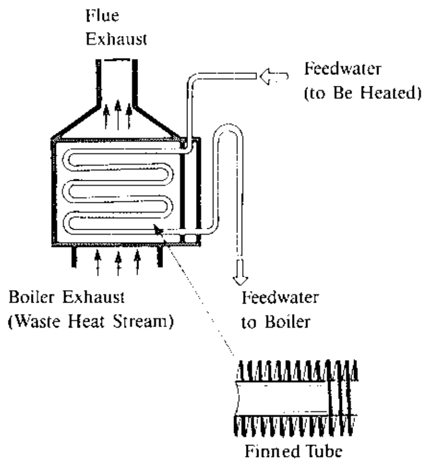
Waste Heat Boiler for Heat Recovery from Gas Turbine or Incinerators
Figure 12

Finned Tube Heat Exchanger

This gas/liquid heat exchanger (Figure 13) consists of a long convoluted tube. The liquid to be heated flows through the tube and the exhaust gases, containing waste heat, flow over the tube. Fins attached to the external tube surface provide additional surface area for transferring heat, thus compensating for the lower film heat transfer coefficients of the gases.

This type of heat exchanger is commonly used for heating water. Boiler flue gas economizers are the most common application, normally being used to heat the boiler feed water.

Typical efficiencies are 40 to 60 percent.

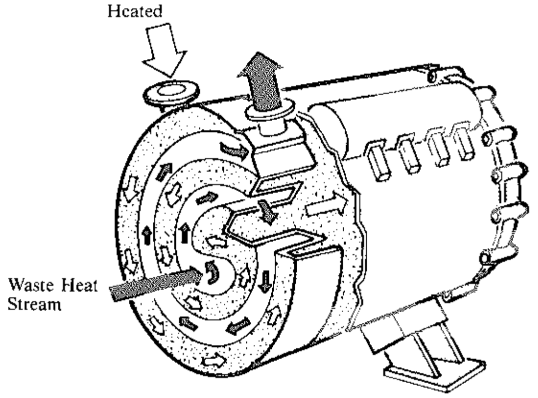


Finned Tube Heat Exchanger
Figure 13

Spiral Heat Exchanger

This heat exchanger consists of two relatively long plate metal strips that are concentrically rolled to form a pair of separated leakproof spiral channels (see Figure 14). They offer greater compactness, and lower fouling characteristics when compared with shell and tube units.

Spiral heat exchangers are frequently used for handling dirty cooling water and are effective for recovering heat from atmospheric pressure steam. For example, a spiral heat exchanger could be used to condense atmospheric steam from open cookers to heat hot water for cleaning operations. Typical heat recovery efficiency is in the range of 60 to 65 percent.



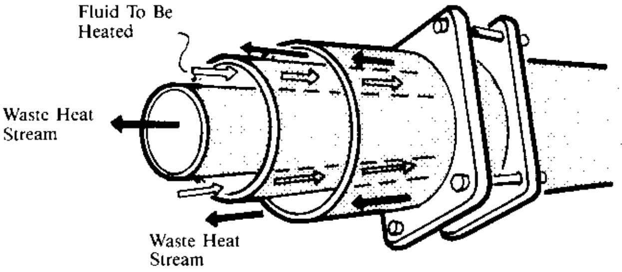
Spiral Heat Exchanger
Figure 14

Concentric Tube Exchanger

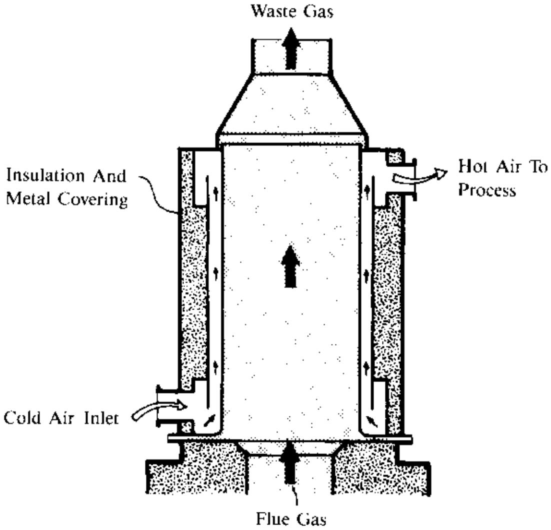
This type of heat exchanger consists of two or three concentric tubes. The heating or cooling fluid flows through the inner tube, and the product to be heated or cooled flows in the second tube. If three tubes are used, the heating or cooling fluid flows in the outer tube as well. Figure 15 depicts a three-tubed tubular heat exchanger.

This type of exchanger must be completely dismantled when an inspection for leakage or fouling is needed. Although these exchangers may be difficult to maintain, they are easily cleaned in place. Heat recovery applications include those involving a viscous liquid or a liquid with solids in suspension. When liquids are used, the permissible solids content may be as high as 40 percent. Gas/gas applications include radiative recuperators, i.e. preheating air with hot flue gases (Figure 16).

As these units have pure counterflow, heat transfer efficiencies are high; typically in the range of 60 to 70 percent.



Concentric Tube Exchanger
Figure 15



Metallic Radiation Recuperator
Figure 16

Plate Heat Exchangers

These passive systems consist of alternate channels through which the hot and cold streams flow, separated by a thin wall of metal or other materials. The two streams may pass in parallel flow, counter flow, or cross-flow arrangements, all without contamination.

The plate and frame heat exchanger is generally used in liquid/liquid or steam/liquid applications. These units consist of a metal frame in which a variable number of corrugated metal sheets are clamped together (see Figure 17). The two fluids flow in alternate channels in the plates, usually in a counterflow directions. Plate corrugations produce turbulence and an increased surface area, thus improving heat transfer efficiency. Plates are usually constructed from stainless steel, titanium, Hastelloy or Incoloy. Adjoining plates are spaced apart and gasket sealed to prevent leakage and intermixing. Gasket material includes viton, Buna N, EPT or asbestos. The total surface area of the exchanger can be readily adjusted by the addition or removal of plates.

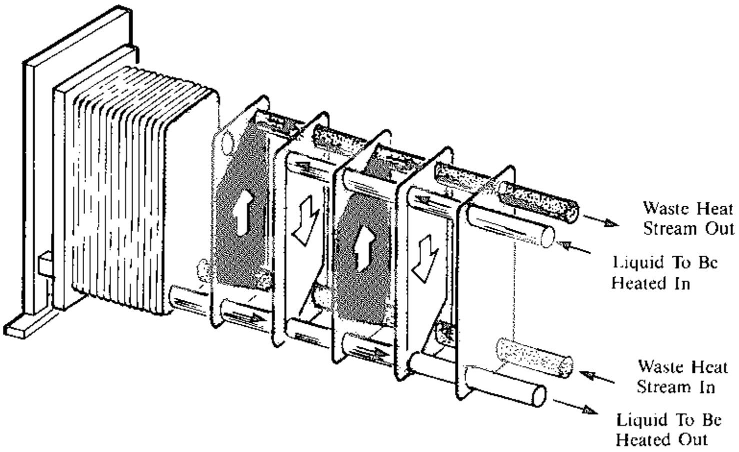


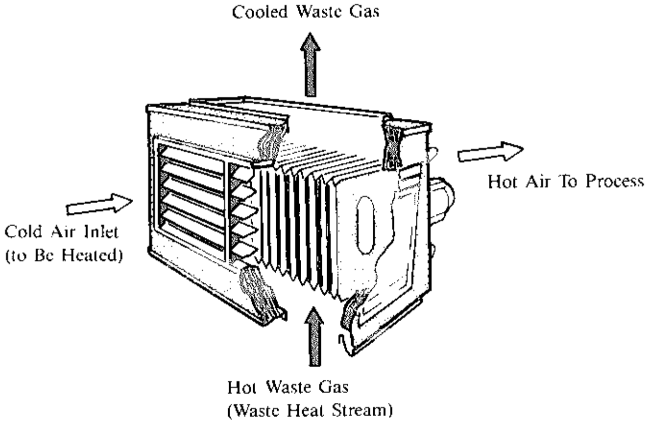
Plate Heat Exchanger
Figure 17

Plate and frame heat exchangers are simple, and easy to clean, inspect and maintain as there is ready access to the heat transfer surfaces. They can be easily cleaned in place by flushing with chemical solutions. For these reasons plate heat exchangers are a suitable choice for applications that directly involve potable water or food products. However, maintenance of gaskets is a major problem. Use is generally limited to liquids having less than 5 percent solid particle content and particle sizes below 1 mm in diameter in order to minimize the possibility of plugging.

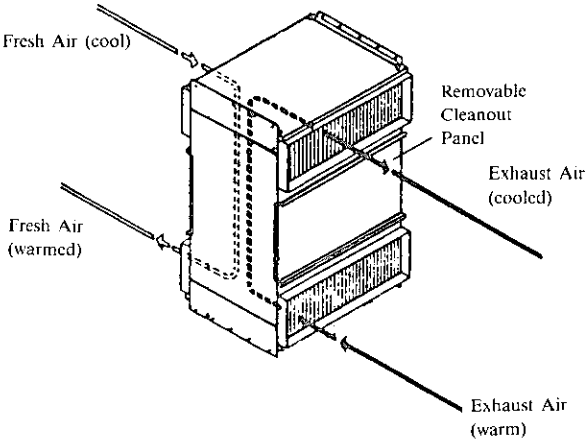
Typical heat recovery efficiencies for plate exchangers are in the order of 75 to 80 percent.

Depending on the size and number of plates used, these exchangers can handle flows in the range of 1.0 L/s to over 170 L/s. Maximum pressure drops through the units generally range from 1800 to 3200 kPa. Upper temperature limits are generally 240°C.

Plate heat exchangers used for most gas/gas applications are of the type referred to as fin type plate heat exchangers. The basic fin type heat exchanger is a cross-flow design (Figure 18). A second configuration is the counter-flow unit known as a Z-box (Figure 19). Counterflow airstreams provide the greatest temperature difference for maximum heat transfer, but a cross flow design can sometimes give more convenient airstream duct connections. Fin type plate heat exchangers are generally used in situations where air temperature is less than 500°C. Proper sealing and gasketing prevents cross-contamination and the unit can be easily cleaned, maintained and inspected. Applications include heat recovery from baking, drying and curing ovens and from heating and ventilation systems.



Air-to-Air Plate Heat Exchanger
Figure 18



Z-Box Heat Exchanger
Figure 19

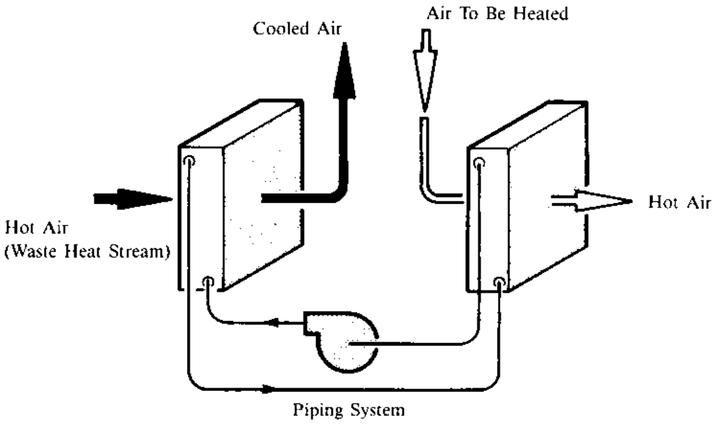
Heat recovery efficiencies for the cross flow and counter flow configurations are in the range of 40 to 60 percent and 65 to 75 percent, respectively.

It is difficult to develop a general range of airstream velocities and pressure drops for all types of fin type, fixed plate heat exchangers as applications and construction methods are widely varied. However, typical capacities of the fin type module units are in the order of 470 to 4,700 L/s. Larger capacity can be built using modules and can be as high as 47,000 L/s.

Run-around System

The run-around coil system can be effective for waste heat recovery from air streams, particularly when it is desirable to install a heat recovery system without re-routing ductwork. This system is also suited to situations where a large distance exists between the waste heat source and demand. Complete separation of the airstream eliminates the possibility of cross contamination between the outside airstream and the exhaust airstream(s).

In its simplest form, used for low-temperature process heat recovery, it consists of finned-tube water coils with a circulating pump and connecting piping. As illustrated in Figure 20, one coil is located in the exhaust gas stream, and the other is located in the duct through which the air to be heated is flowing. Several coils may also be connected in series or parallel to serve several heat sources and use locations. The pump is used to circulate a heat transport fluid such as water, glycol (antifreeze) solution, or a higher temperature heat transfer fluid through the two coils.



Runaround System
Figure 20

The temperature range of run-around coil exchangers is limited by the thermal transfer fluid. At higher temperatures (above 200°C), special coil construction and control systems may be required to ensure a permanent bond of the coil fins to the tubes and to prevent the transfer fluid from reaching excessive temperatures.

In many cases, demineralized water can serve as the heat transfer medium. This is preferred since pure water offers high heat transfer efficiency. Water is limited in application because of the high freeze point. In addition to concerns regarding corrosion, this has created the need for other heat transfer fluids such as corrosion inhibited glycol solution.

Specific recommendations for a given application should be sought from the appropriate fluid manufacturer. When standard finned-tube water coils are used, coil engineering data should be used to determine air pressure drops for a specific design. Coil face velocities are typically in the 1.5-3.0 m/s range. Lower face velocities may result in first cost penalties. Higher face velocities may result in operating cost penalties because of higher airstream pressure drops.

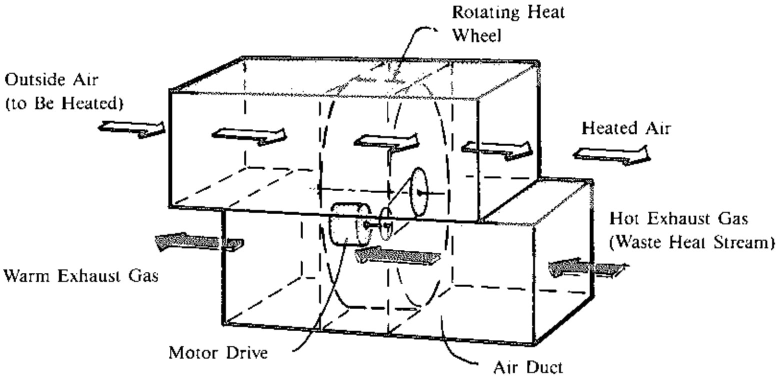
Pressure drops of the high temperature round spiral-finned tube coils range from .005 to 1.0 kPa, depending on the fin spacing and the number of passes.

Applications with exhaust temperatures up to 200°C can normally achieve sensible heat recovery efficiencies of 60 to 65 percent. Applications in excess of 200°C usually attain slightly lower sensible heat efficiencies of up to 50 percent, due to the reduced heat transfer capabilities of the thermal fluids and materials of construction.

Heat Wheels

The heat wheel (also called a rotary regenerator) is becoming increasingly popular for use in low to medium temperature, air/air waste heat recovery applications. Shown in Figure 21, it contains a sizable porous disc, fabricated from material having a high heat capacity, which rotates between two side-by-side ducts; one a cold air duct, the other a hot air duct. The axis of the wheel is located parallel to, and on the partition between the two ducts. As the wheel slowly rotates, sensible heat (and in some cases, moisture containing latent heat) is transferred to the material by the hot air and removed from the material by the cold air.

The air duct connections (Figure 21) are arranged so that each of the airstreams flows axially through approximately one-half of the wheel in a counter-flow pattern. The porous media that is heated from the warm duct airstream, rotates into the cold duct airstream where it releases the newly obtained energy.



Heat Wheel or Rotary Regenerator
Figure 21

Heat wheels are built typically in the range of 3.5 meters in diameter with air capacities up to 30,000 L/s. However, wheels as large as 15 m in diameter have been built. Multiple units can be used in parallel.

Heat wheels are available for temperatures from -50°C to 870°C. By application and design, they can be broadly divided into two categories — "comfort" applications and "process" applications.

- Comfort — Comfort applications are designed for transfer of either sensible heat or total heat at temperatures from -50°C to about 90°C maximum. The media is made of metal, mineral or man-made materials.
- Process — Low temperature process applications are for sensible heat transfer at temperatures up to approximately 200°C. The media is usually made of aluminum. However, stainless steel, monel and other corrosion-resistant materials may be used for corrosive atmospheres. Medium temperature process applications are used for temperatures up to 425°C.

  The media is made of stainless steel, monel or other similar materials and ceramic materials. High temperature process applications can be used up to 870°C. The media is made of either ceramic materials or high temperature-resistant steels.

Heat wheels are available in four configurations. The first consists of a metal frame packed with a core of knitted mesh stainless steel or aluminum wire, resembling that found in the common metallic kitchen pot scraper.

The second type, called a laminar wheel, is fabricated from corrugated metal and is composed of many parallel flow passages.

The third type is also a laminar wheel but is constructed from a ceramic material in a honeycomb configuration. This is used for higher temperature applications with a present operating limit of about 870°C.

The fourth variety is of laminar construction, but the flow passages are coated with a water absorbing material so that both latent and sensible heat may be recovered. The packing of the wheel may be any of a number of materials, lithium chloride being an example.

The overall efficiency of sensible heat transfer can be in the range of 70 to 80 percent. With this type of wheel, the total quantity of heat recovered (i.e. both sensible and latent heat) is in the range of 65 to 80 percent.

The performance of an air-to-air rotary heat exchanger may be characterized by the pressure drops occurring in the airstreams and by the efficiencies of the unit. Both are functions of the face velocity which is based on the area exposed to the airflow. The total face area of the wheel is divided in half, with each half being used by one of the two airstreams.

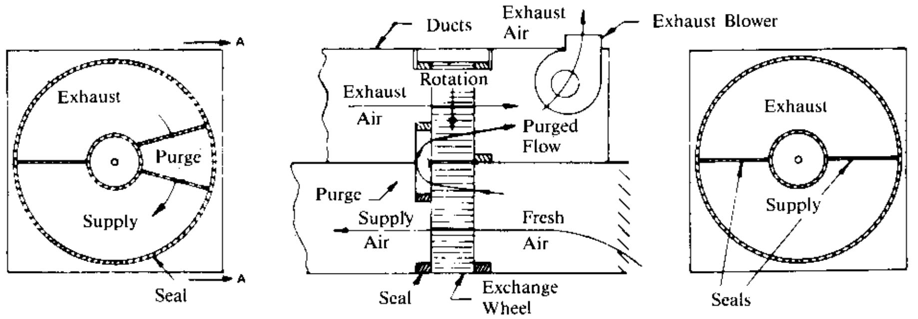
Practical face velocities for comfort applications are in the 2.0 to 4.6 m/s range. Low velocities normally result in lower pressure drops, higher efficiencies and lower operating costs, but require larger size units and more space for installation.

Higher airstream velocities offer lower initial costs and smaller space requirements, but operating costs are usually higher as a result of the increased pressure drops.

For optimal performance, comfort wheels are constructed from .150 m to .30 m thick. High temperature wheels may be as thin as 0.1 m or as thick as 1.0 m, depending on the allowable pressure drop of each of the two airstreams. They generally rotate at a rate of 5 to 20 rpm.

Since the pores of heat wheels carry a small amount of gas from the exhaust to the intake duct, cross contamination can result. If this contamination is undesirable, the carryover of exhaust gas can be partially eliminated by the addition of a purge section (Figure 22) where a small amount of clean air is blown through the wheel and then exhausted to the atmosphere, thereby clearing the passages of exhaust gas.

Heat wheels are finding increased use for process heat recovery in low and moderate temperature environments. Typical applications would be in curing or drying ovens and boiler air preheaters. These are also well suited to space heating situations where unusually large quantities of ventilation air are required for health or safety reasons.



Building Side (Inside Face)
Upstream Exhaust
(Downstream Supply)

Vertical Cross Section (A-A)
Wheel, Seals and
Purge Section

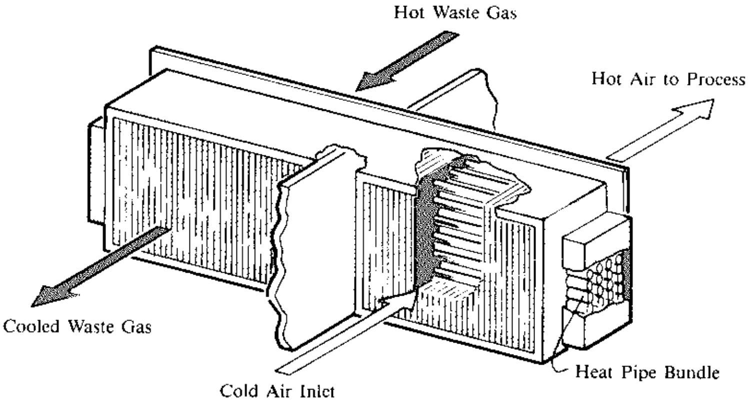
Weather Side (outside Face)
Downstream Exhaust
(Upstream Supply)

Heat Wheel with Purge Section
Figure 22

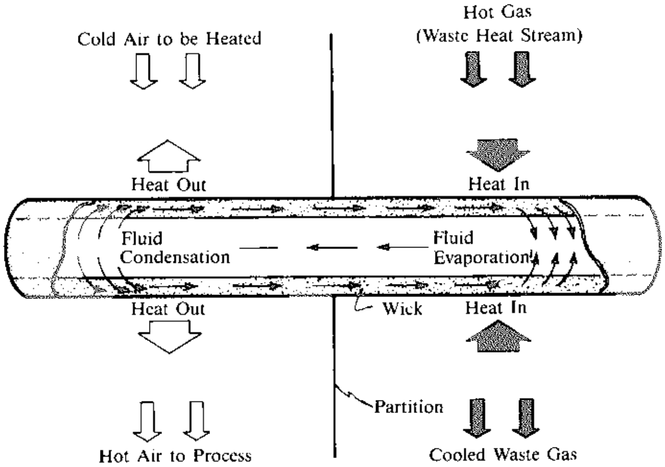
Heat Pipes (Thermosiphon Heat Exchangers)

The heat pipe is a passive, gas-to-gas, finned-tube heat exchanger. As can be seen in Figure 23, the elements form a bundle of heat pipes which extend through exhaust gas and inlet air ducts in a pattern that resembles the structured finned coil heat exchangers. Each pipe, however, is a separate sealed element with an annular wick inside and extending the full length of the tube (Figure 24), in which an appropriate heat transfer fluid is sealed. Although the heat pipes span the width of the unit, a sealed partition separates the two airstreams, preventing any cross-contamination between them.

The heat pipe is compact and efficient as the evaporative-condensing cycle within the heat tubes is a highly efficient way of transferring heat. Heat absorbed from hot exhaust gases evaporates the heat pipe fluid at the hot end pushing vapour to the cold end. The latent heat of vapourization is carried in the vapour to the cold end of the heat pipe located in the cold gas duct. Here the vapour condenses giving up its latent heat. The condensed liquid is then carried by capillary (and/or gravity) action through the wick back to the hot end where it is again vapourized.



Heat Pipe System
Figure 23



Heat Pipe
Figure 24

Heat pipes are available to operate in the range of temperatures from -50°C to 700°C. Units that operate up to 275C are manufactured from aluminum, copper and steel, while the higher temperature units are usually made of steel.

Heat recovery efficiencies for these devices range from 40-70 percent depending on the application. An efficiency of 60 percent is a typical value.

Heat pipe heat exchangers should be operated with counter flow airstreams for maximum efficiencies. However, they can be operated with parallel airstreams at reduced efficiencies. For example, a heat pipe heat exchanger operating at 60 percent efficiency with equal mass flows in a counter flow arrangement will operate at 48 percent efficiency with equal mass flows in a parallel flow arrangement. As a rule of thumb, parallel flow efficiencies can be estimated to be 80 percent of counter flow efficiencies.

Design face velocities for heat pipe exchangers range from 2.0 to 4.0 m/s, with 2.3 to 2.8 m/s most common. Pressure drops at 60 percent efficiencies (sensible) range from .10 to .175 kPa at 2.0 m/s up to .375 to .50 kPa at 4.0 m/s. Recovery efficiencies decrease with increasing velocity, but the effect is not as pronounced as with pressure drop.

Applications for these devices include preheating air for dryers and ovens and preheating combustion air for boilers.

Heat Pump Equipment

Heat pumps are waste heat upgrading devices and as such, involve raising the temperature of a waste heat stream to that required.

Heat pumps use an external energy source (such as electricity) to increase the temperature of the recovered waste heat. This system works basically as a reverse refrigeration cycle. The liquid in the evaporator absorbs heat from the waste heat source and vaporizes; the vapour is then compressed raising the temperature. From there, it goes to the condenser where the previously absorbed heat is given up to the fluid to be heated.

Heat Pump Types

Heat pumps are commonly classified by the type of heat source and heat sink. Various heat source and heat sink arrangements are possible, depending on the form of the waste heat. Those used in waste heat recovery applications include:

- Air-to-Air
- Water-to-Air
- Air-to-Water
- Water-to-Water

In each of the above, cases, the first term refers to the heat source and the second term refers to the heat "sink" or stream that will receive the extracted heat.

The air-to-air heat pump is the most common type and is widely used in residential and commercial space heating applications. Heat is extracted from an outside or exhaust air stream and is upgraded and transferred into a space.

A water-to-air heat pump utilizes water as the heat source and uses air to transmit heat to the conditioned space.

Air-to-water heat pumps are commonly used to produce hot water in industrial applications. These systems extract heat from exhaust air and transfer it to water.

A water-to-water heat pump extracts heat from a water source while simultaneously rejecting heat to a water heat sink, to either heat space or process.

Heat Pump Components

For the most part, the components and practices involved with heat pumps relate directly to refrigeration. These have been covered in detail in Manual 11 of this series "Refrigeration and Heat Pumps". Figure 4 of this manual presented a schematic presentation of a heat pump.

The main components are:

- Refrigerant compressors
- Evaporators
- Throttling devices
- Condensers

Compressors:

Displacement and dynamic compressors are commonly used for heat pump applications.

Displacement machines increase the working fluid pressure by reducing the volume of the compression chamber. This is done by applying shaft work to the mechanism. This category includes:

- Reciprocating compressors
- Rotary (Vane) compressors
- Screw (Helical Rotary) compressors

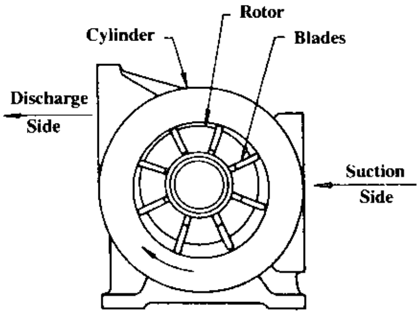
Dynamic compressors increase refrigerant pressure through a continuous exchange of angular momentum between a rotating mechanical element and the fluid being compressed. This type includes:

- Centrifugal compressors
- Turbo compressors

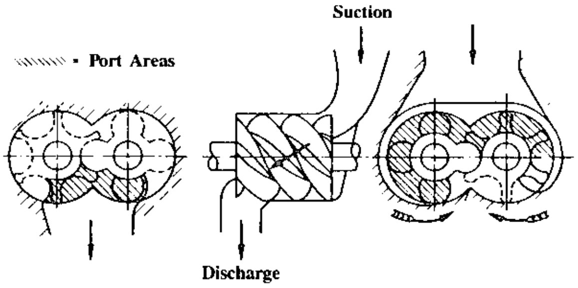
Figure 25 diagramatically presents several of the above compressors.

Of the types listed above, reciprocating compressors are the most widely used. This is primarily because:

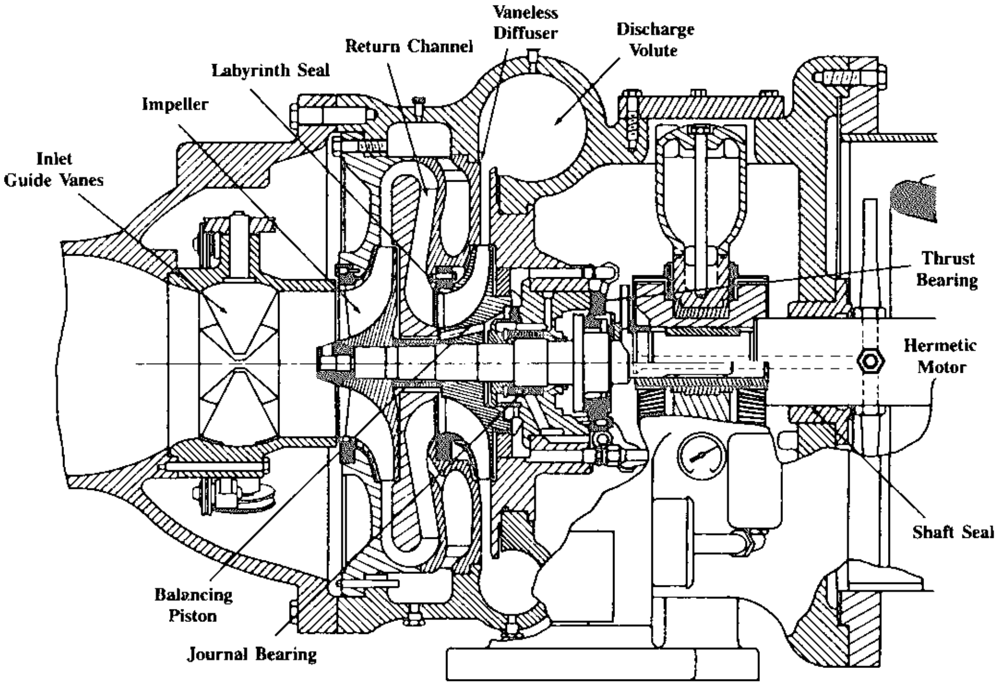
- they are efficient through a wide range of loading;
- they are available in a full range of sizes and capacities, and;
- they are relatively inexpensive.



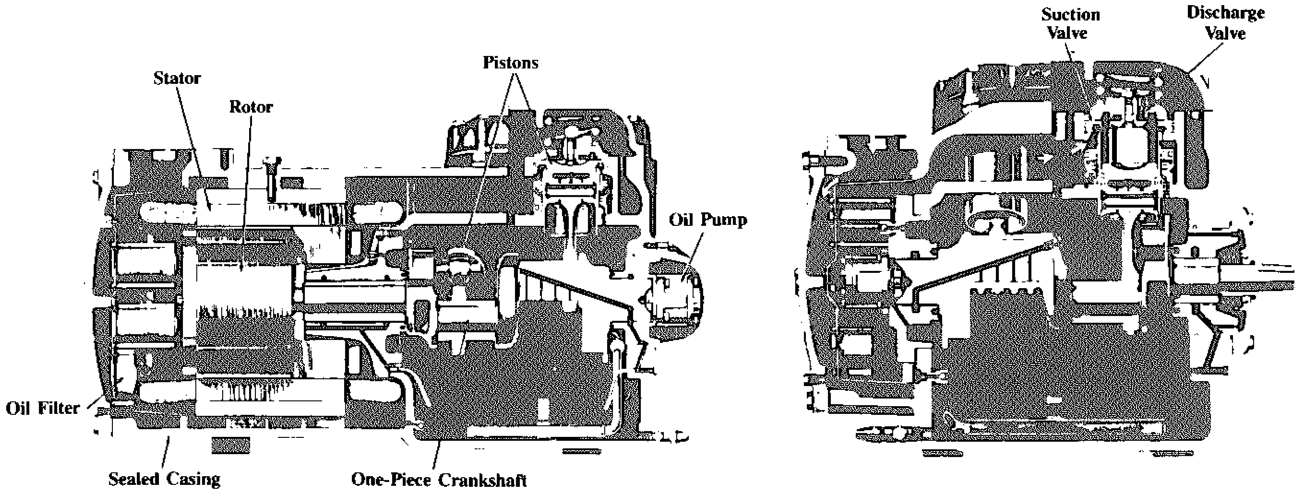
Interior View Of A Large Rotary Compressor



Helical Rotary Twin Screw Compressor



Centrifugal Refrigeration Compressor



Hermetic Compressor

Typical Reciprocating Compressors

Open Type Compressor

Heat Pump Compressor

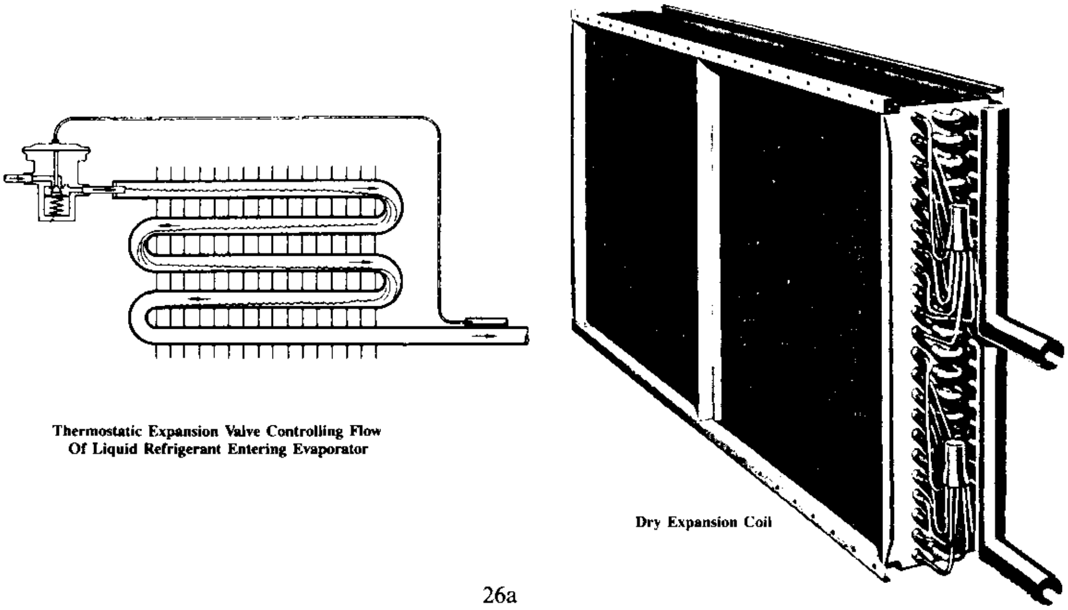
Figure 25

Evaporators and Condensers:

Evaporator and condenser selections depend on the form of the waste heat source (gas or liquid) and the intended heat sink (again gas or liquid).

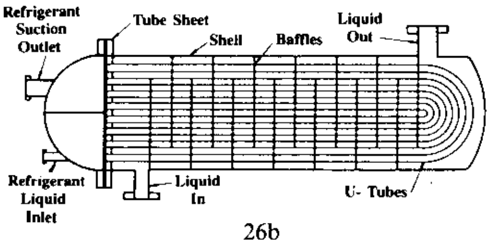
Evaporators commonly used include:

- Direct Expansion Coils consisting of a series of finned tubes through which the refrigerant flows. This type is used to extract heat from gas streams (see Figure 26a).
- Shell and Tube Heat Exchangers (discussed previously). These are used to extract heat from liquid, waste process streams, etc. The refrigerant flow is generally through the shell and the liquid is through the tubes (see Figure 26b).


Thermostatic Expansion Valve Controlling Flow Of Liquid Refrigerant Entering Evaporator

Dry Expansion Coil

26a
Direct Expansion Coil Details



26b
Direct (U Tube-Type) **Expansion Liquid Cooler**

Heat Pump Evaporators
Figure 26

As with evaporators, condensers used in heat pump application are generally one of the above two forms.

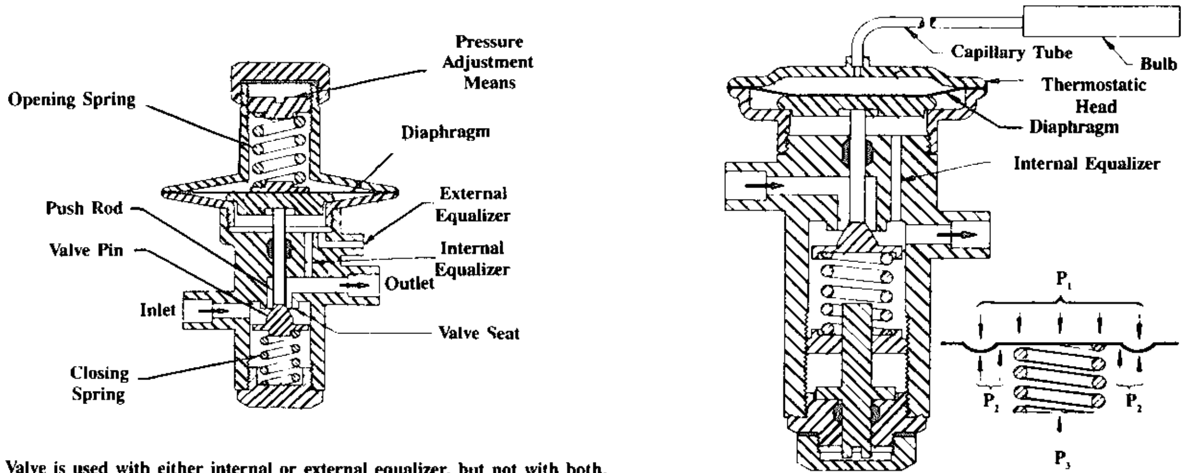
Throttling Devices:

Throttling devices (expansion valves) are used to control the flow of liquid and lower the pressure of the refrigerant to the evaporator of the heat pump.

Two types are used:

- The constant pressure expansion valve which maintains a constant load on the compressor (Figure 27a).
- The thermostatic expansion valve which meters the flow of refrigerant to the evaporator, so as to match system capacity to load (Figure 27b).

Of the two types, the latter is most commonly used because of its operating flexibility.



Valve is used with either internal or external equalizer, but not with both.

Constant Pressure Expansion Valve
27a

P_1 - Thermostatic Element's Vapor Pressure
P_2 - Evaporator Pressure
P_3 - Pressure Equivalent Of The Superheat Spring Force

Thermostatic Expansion Valve
27b

Heat Pump Expansion Valves
Figure 27

Courtesy of ASHRAE

Heat Pump Applications

Heat pumps offer flexibility in application, as they use an indirect method for recovering and supplying heat. They are used primarily for space heating and for process and water heating.

High temperature heat pumps have recently become available commercially. These units are able to use waste heat streams with temperatures as high as 40 to 70°C. Comparatively, conventional heat pumps generally use heat sources with temperatures in the range of 5 to 20°C. As a typical application, high temperature heat pumps are being used in some chemical processing industries to extract heat from the distillation columns overhead vapours and apply the heat back to the column itself. While the technology is still relatively new and is currently limited to certain industries, high temperature heat pumps hold great promise in waste heat recovery projects in the not too distant future.

Vapour Recompression

Vapour recompression is a form of heat pumping in which waste vapour from a process is compressed to raise its temperature. This heat is recycled to the process source or used elsewhere. It is more efficient than conventional heat pumping but less flexible as only vapour source waste heat can be recovered. Vapour recompression can be accomplished through mechanical and thermal compression.

Mechanical Recompression

Detailed information regarding compressors is contained in Module 14, Compressors and Turbines, in this series. The following is a description of compressors as they relate to waste heat upgrading.

The compressor is the most important item included in any mechanical vapour recompression (MVR) system. Great care should be taken to insure that the right type of compressor is chosen and that the compressor has the flexibility to operate under all conditions required of the system.

There are a wide variety of compressor types:

- Screw Compressors:

  A screw compressor is a positive displacement machine consisting of two mating helical grooved rotors (male and female) enclosed in a stationary housing with suitable inlet and outlet ports. This compressor has limited applications due to low volumetric handling capacities. It does, however, offer significant pressure ratios. It is not particularly suited to partial load conditions.

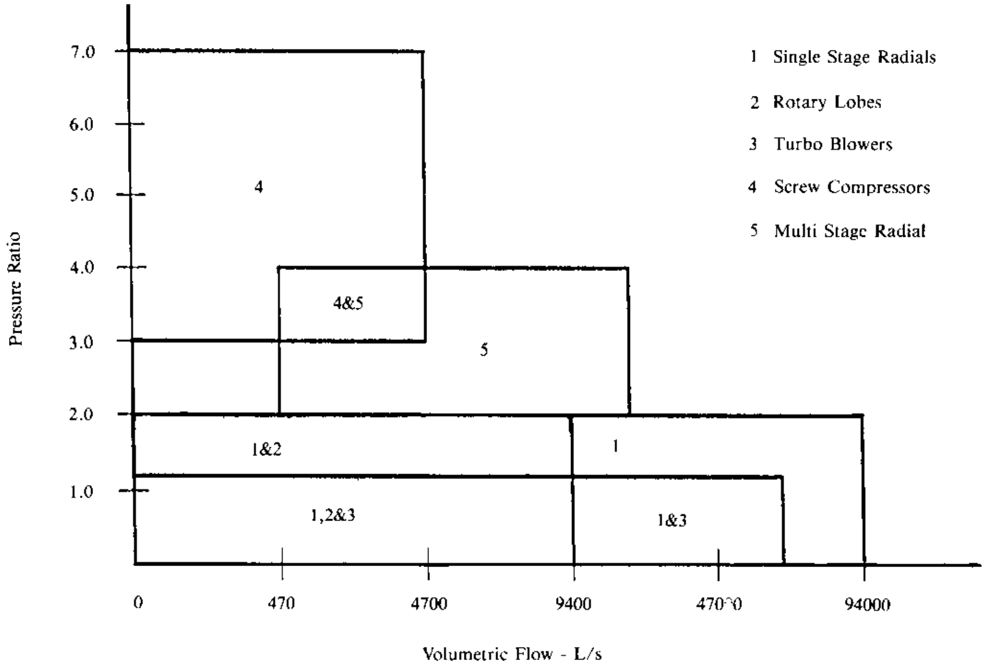
- Rotary Lobe Compressor:

  The rotary lobe compressor is a positive displacement machine consisting of a casing containing duplicate symmetrical rotors in stationary housing. The two rotors are kept in timing by external gears. Sealing within the stationary housing and between rotors is by close clearance. These machines are used in low volumetric applications where pressure ratios of 2 to 1 are acceptable.
- Turboblowers (Fan):

  This compressor type is gaining increased popularity for use in MVR systems. A welded casing and low operating speed allow for a wide choice of materials of construction and low capital costs. This is not a conventional air handling fan, but a unit specifically designed for steam applications. The unit is capable of pressure ratios of 1.2 to 1.3:1 and a volumetric capacity to 70,000 L/s.
- Single Stage Radial (Centrifugal Type):

  The single stage radial compressor is the most widely used compressor in MVR service. Their wide range of operation and relatively low price per unit flowrate make them attractive for medium and large MVR evaporators. Radial compressors are more efficient than rotary lobe type compressors but not as efficient as turbo blower. Capacities up to 95,000 L/s are possible with a maximum pressure rise limited to the 2.0 to 2.1 range.

Figure 28 shows relative capacities and pressure ratios for different types of compressors.



Compressor Capacities
Figure 28

Electric motors (both constant and variable speed) are commonly used for driving compressors. Steam turbines can be cost-effective for large applications where high pressure steam is available.

While the theoretical compressor power requirements are reduced slightly by going to lower evaporating temperatures i.e., by operating in the subatmospheric pressure range, the volume of vapour to be compressed and hence the compressor size and cost increase so rapidly that such operation is more expensive than high-temperature operation.

Thermal Recompression

This method is most suited for sub-atmospheric vapour compression and can handle large vapour volumes at low capital costs. It is commonly used for evaporation in food processing applications, where low temperatures must be maintained during evaporation to preserve product quality, and motive steam is available at an acceptable pressure.

Thermal compression results in a larger vapour mass than the low grade vapour, but systems can be designed to use this energy completely. Contamination of the condensate is another concern, and in most cases, disposal is the only choice.

The design of jet ejector is described in Module 8, ''Steam and Condensate Systems'', and the reader is referred to that module for more details.

Vapour Recompression Applications

In most cases, vapour recompression, thermal or mechanical, is used where:

- Waste heat temperature is in excess of 70°C;
- Temperature of upgrade does not exceed 10°C;
- Waste heat availability and use are simultaneous and quantities are well matched.

The limitation on the temperature of upgrade is imposed by the design of compressors. Turbocompressors are normally selected for vapour compression as these can operate under variable volume conditions, producing constant discharge pressure. However, for water vapour compression, a large number of stages of compression are required at pressure ratios greater than 1.5, normally making heat upgrading by more than 10°C uneconomic.

Consumption of motive steam increases substantially at upgrade temperatures greater than 10°C for thermocompressors. However, these may still be suitable if the required quantities of upgraded heat substantially exceed low-grade heat available.

Application of vapour compression for variable source or load applications is also not favoured as vapours cannot be stored economically.

Despite these limitations, vapour compression has found wide use in process application because of the high COP's obtained. Thermocompression, where applicable, can be highly economical because of the low cost of thermocompressors. An example is the compression of flash steam discharged from the condensate drum for process use.

Multi-Stage Operations

Multi-stage operations are a means of obtaining energy cascades in a production process involving heating or cooling. Examples of conventional multi-stage operators include:

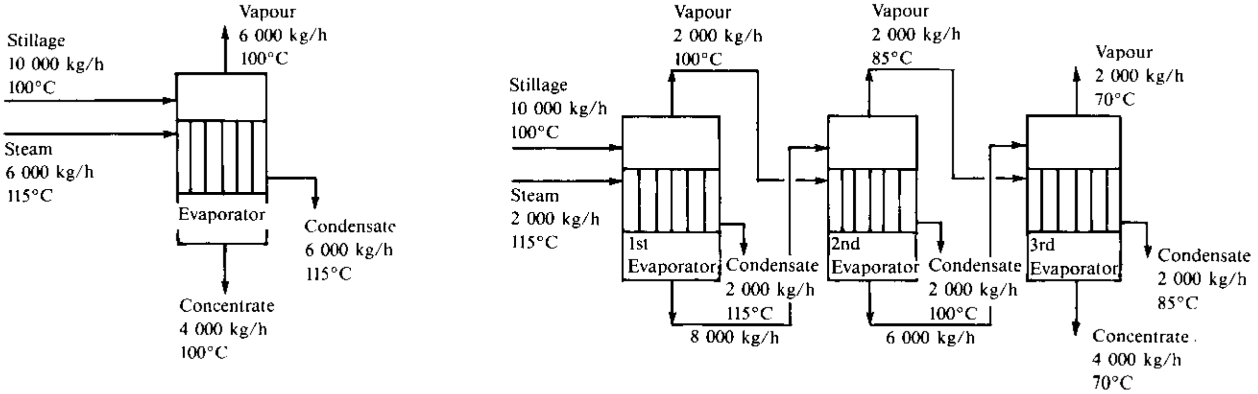
- Multi-Effect Evaporation
- Steam Flashing
- Other Multi-Stage Operations

Multi-Effect Evaporation

Evaporation is the removal of a solvent from a solution or slurry by the vaporization of the solvent. In early all industrial applications, the solvent is water and the nonvolatile residue is the valuable constituent. The single-effect evaporation is the simplest evaporator arrangement. It uses steam from an outside source and exhausts its vapor to the atmosphere or to an air or water cooled condenser. Such an evaporator requires about one kilogram of steam per kilogram of water evaporated — somewhat more if the need is colder than the product.

Energy efficiency can be improved by using multiple-effect evaporation. Figure 29 presents an example of a triple effect system for distillery stillage evaporation. In this operation, the vapor from the first effect is used to heat the second effect, boiling at a lower temperature (and pressure). The vapor from the second effect is used to heat the third effect, boiling at a still lower temperature (and pressure). Vapors from the third effect are condensed in a condenser.

In the above example, a 66 percent reduction in energy use can be achieved by replacing the single effect system with a three effect system.



Single Effect Evaporation

Triple Effect Evaporation
Steam Saving = 4 000 kg/h

Multi-Effect Evaporation
Figure 29

Evaporators are available in numerous designs and selection is dependent on properties of the material to be evaporated, the overall process configuration and the final concentration required. Retrofit involves increasing the number of effects and normally using an evaporator of the existing design. Large evaporators having six or seven effects have been commonly used in the pulp and paper industry and more recently in the food industry.

Multi-Stage Steam Flashing

When a high pressure condensate is discharged to a lower pressure it contains more heat than necessary to maintain the liquid phase at that lower pressure. As a result, the excess heat causes some of the condensate to vaporize at the lower pressure as flash steam. By releasing condensate at a specified pressure, useful steam can be produced.

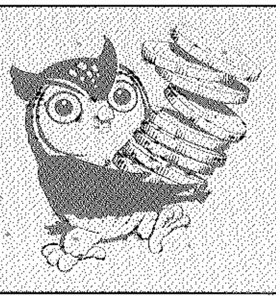
Multi-stage flashing involves flashing down high pressure condensate in stages to generate steam for intermediate uses. Ideal conditions for flashing exist when high pressure condensate is available, steam is required at lower pressures, and excess steam is being wasted in the steam drain. Even in cases where no waste takes place, steam flashing can reduce steam use by increasing the heat recovery efficiency of the boiler economizer.

Steam flashing and related equipment have been described in detail in Module 7 of this series, "Steam and Condensate Systems". The reader is referred to that manual of additional information.

Other Multi-Stage Operations

Multi-stage operations can be considered for a variety of applications. By interconnecting equipment or processes through the use of heat exchangers, heat pumps etc, it is possible to extract heat energy from a waste heat source. An example is two-stage drying of food products using dryer exhaust gases with low relative humidity to pre-dry a product in specially designed equipment. A new indirect dryer, being proposed for the distillery and pulp industries, uses high pressure steam while generating low pressure vapor which can in turn be used for multi-stage evaporation.

ENERGY MANAGEMENT OPPORTUNITIES



Energy Management Opportunities is a term that represents the methods by which energy can be used wisely to save money. A number of typical Energy Management Opportunities, subdivided into Housekeeping, Low Cost, and Retrofit categories are outlined in this section with worked examples to illustrate the potential energy savings. This is not a complete listing of the opportunities available for waste heat recovery. However, it is intended to provide ideas for management, operating and maintenance personnel to allow them to identify other opportunities that are applicable to a particular facility. Appropriate modules in this series should be consulted for Energy Management Opportunities existing with other types of equipment and systems.

Housekeeping Opportunities

Housekeeping opportunities are Energy Management actions that are done on a regular basis and never less than once a year. The following are typical Energy Management Opportunities in this category:

- **Identification of Waste Heat Sources**

  While seemingly a simple task, the importance of identifying sources of waste heat cannot be over emphasized. Managers and operating staff should be constantly on the watch for waste heat sources. Particular attention should be paid to any existing process or system that is replaced or modified.

- **Elimination of Waste Heat Sources**

  Outright elimination of waste heat sources is often possible. Typical examples would include:

  - checking for and eliminating steam leaks. While seemingly small, steam leaks waste steam and consequently money. Module 9, "Heating and Cooling Equipment (Steam Water)" presents an excellent example of the typical cost savings that can be achieved when leaks are eliminated.
  - proper functioning of steam traps. As with steam leaks, improperly functioning steam traps can waste large quantities of heat. They can also have a negative impact on production processes. Inspection of traps should be part of any maintenance program.
  - inspection and maintenance of insulation. Insulation is a cost effective means of reducing waste heat. Damaged or missing insulation should be repaired and replaced. Special attention should be paid to any process or equipment that has been changed or modified.
  - shutting down equipment and systems when not required. The rationale for leaving infrequently used equipment running on a continuous basis should be reviewed. If it is not possible to turn the equipment off during inactive periods (i.e. overnight), rescheduling of process operations helps to reduce energy consumption and hence waste heat. Alternatively, more efficient, faster acting equipment might be considered.

- **Minimization of the Heat Content of Waste Heat Streams through Maintenance Control Mechanisms**

  Sometimes, the complete elimination of a waste heat stream is not always possible nor desirable. For example, it may be desirable to keep flue gas temperature above a certain point in order to prevent condensation problems. In other situations, the heat content of the waste stream can be lowered without any adverse effect on the process. Periodic evaluation of operating temperatures and practices is required. Setpoints should be appropriately adjusted. On a more regular basis, control equipment mechanisms should be checked and readjusted as necessary.

- **Maintenance of Mechanical Equipment**

  Proper maintenance of mechanical equipment can lead to a reduction in waste heat. Particular attention should be paid to all heat transfer and heat exchange surfaces. While heat exchange equipment is sized to take into account a given amount of fouling of the system, excessive amounts of fouling can greatly reduce the overall efficiency of the system.

Low Cost Opportunities

Implemented low cost opportunities are Energy Management actions that are done once and for which the cost is not considered great. The following are typical Energy Opportunities in this category.

1. Direct use of clean, waste heat streams.
2. Using waste process water as a heat source for a heat pump in space heating applications.
3. Re-use of exhaust air for drying purposes.

Low Cost Worked Examples

1. **Direct Use of Waste Heat**

Often times waste heat is contained in a clean waste stream that is discharged to the atmosphere or drain. Such situations represent excellent opportunities for direct reuse.

Example: In an actual case history, a major brewery realized that it sent an average of 7.5 L/s (approximately 650,000 L/day) of warm, clean water down the drain.

One of the larger sources was cooling water from the compressor.

Over 100,000 L/day was being discharged at a temperature of approximately 8°C. Reuse of this water for boiler feedwater in a once through system was considered. Feedwater must be heated to 104°C. City water previously used for the purpose averaged 4°C.

a) Heat Saved Per Day:

$$\begin{aligned} Q &= M \times cp \times DT \\ &= 100{,}000 \text{ kg/d} \times 4.18 \text{ kJ/kg}\cdot{}^\circ\text{C} \times (8\text{-}4)^\circ\text{C} \\ &= 1{,}672{,}000 \text{ kJ/day is the amount of energy saved per day} \\ &= 1{,}672{,}000 \text{ kJ/day} \times 250 \text{ days/year} \\ &= 4.18 \times 10^8 \text{ kJ/year} \end{aligned}$$

b) Calculation of Natural Gas Cost Savings:

If natural gas costs \$4.27/GJ (\$4.50/mcf)
and is combusted at 90 percent efficiency, then the savings in natural gas costs equates to:

$$= Q \times \frac{1}{E_{boiler}} \times \frac{\$}{\text{Unit Energy Content of Fuel}}$$

$$= 4.18 \times 10^8 \text{ kJ/yr} \times \frac{1}{.9} \times \frac{\$4.27}{\text{GJ}}$$

$$= \$1980/\text{yr.}$$

c) Calculation of Water Cost Savings:

Since the compressor cooling water displaces water used for feedwater, a cost saving for water can be realized. Assuming a water cost of \$3.00/4546 L, the savings in water costs equates to:

$$= \text{Water volume saved} \times \frac{\$}{\text{unit volume of water}}$$

$$= 100{,}000 \text{ L/d} \times 250 \text{ d/yr} \times \$3.00/4546 \text{ L}$$

$$= \$16{,}500/\text{yr}$$

d) Calculation of Payback:

Cost for installing piping to take the compressor cooling water to the boiler was \$30,000.

$$\text{Simple payback} = \frac{\$30{,}000}{\$1{,}980 + \$16{,}500}$$

$$= 1.62 \text{ years}$$

2. Using Waste Process Water as a Heat Source for a Heat Pump

A small office addition was planned for an industrial facility in Toronto and an economical means of heating and cooling the new addition was desirable. The plant rejects waste heat in the form of water with a temperature of 15°C and a flowrate of .38 L/s. Such a situation presented an excellent opportunity for a heat pump application.

Loads for the proposed building, including ventilation, were calculated by an energy consultant to be 35.17 kW cooling, and 29.31 kW heating. A rooftop packaged air conditioning system with electric heating had been proposed. The estimated annual heating cost for the all-electric system would be $2,451.

A water-to-air heat pump was considered as an alternative to the basic, air-conditioning with electric heat, rooftop package initially proposed. The heat pump was selected to meet the design heating and cooling loads, with electric duct heaters for 100 percent backup. The heat pump supplier indicated that the COP for heating at the given water conditions was 2.25. The COP of the heat pump would be similar to the air-conditioner performance in the summer. The source of warm water was available 85 percent of the time during the heating season. Cooling water was available throughout the cooling season. The extra cost for a heat pump package over standard air conditioning with electric heat is estimated at $3,000.

Since the heat pump operates as an air conditioner in the summer, the true savings for installing the unit come only as a result of savings in winter (i.e. reduced heating costs). Cost savings can be determined as follows.

a) Annual Heat Pump Energy Costs:

The cost for heating with the heat pump unit can be broken into two parts. For 15 percent of the season the back-up electrical heat units must be used. The cost for heating in this portion of the year is 15 percent of the $2,451 estimated heating bill (see above). For 85 percent of the heating season, the heat pump can use the warm water as a heat source. Since the heat pump is able to produce 2.25 heating units for every unit of input (electrical) energy used, the cost for heating with the heat pump is determined as follows:

$$\text{Cost} = \frac{.85 \times \$2{,}451}{2.25}$$

Therefore, annual heat pump energy costs are:

$$= \frac{(0.85 \times 2{,}451)}{2.25} + (0.15 \times 2{,}451)$$

$$= \$1{,}294$$

b) Annual savings in heating cost is the difference between what it would have cost to heat the building with electric heat, less the cost to heat it with the heat pump:

$$= \$2{,}451 - \$1{,}294$$
$$= \$1{,}157$$

c) Calculation of Payback:

$$\text{Simple payback} = \frac{\$3{,}000}{\$1{,}157} = 2.6 \text{ years}$$

3. Recycle of Drier Exhaust Gases

A major food processor processes field peas into three concentrated products; protein, starch and fibre. In the final processing steps, the products are individually dried and bagged. A walk-through energy audit indicated that the starch and fibre driers used significant quantities of hot air on a once through basis. A potential waste heat recovery opportunity existed. (The following presents the heat recovery application for the fibre drier; similar conditions and economic's were found for the starch drier.)

An energy consultant was called in to take the appropriate field measurements. Results indicated that the fibre dryer discharged 4,150 L/s at a temperature of 93°C and with a relative humidity of approximately 5 percent. Discussion with the equipment supplier indicated that it was possible to operate the driers at exhaust relative humidities in the order of 30 percent without significant adverse affect on drying rates. By recycling a portion of the dryer exhaust gases, the heat content of these gases could be re-used to the point where the exhaust stream relative humidity equalled 30 percent.

Recycling could best be accommodated by diverting a portion of the dryer exhaust gases back to a point downstream of the furnace for the dryer through a recycle line. Recycling residual product laden gases upstream of the furnace was not recommended as it would have resulted in combustion, thereby adversely affecting product quality. Dampers would be installed in both the recycle line and in the exhaust stack to control the amount of air diverted back through the system.

At an exhaust relative humidity of 20 percent, 83 percent recycle of gases was possible i.e. 3,445 L/s. This equated to a 47 percent decrease in fuel consumption for an annual savings of $18,000. Decreased make-up air requirements yielded a further savings of $5,000/year. A marginal increase in power costs for increased power requirement for the fan would amount to a cost of $400/yr. The cost for making the changes was estimated to be $14,300 including material, labour, engineering, etc.

$$\text{Simple Payback} = \frac{14{,}300}{\$18{,}000 + \$5{,}000 - \$400}$$

$$= .63 \text{ years}$$

Retrofit Opportunities

Implemented retrofit opportunities are defined as Energy Management actions that are done once, and for which the cost is significant. Many of the opportunities in this category will require detailed analysis by specialists and cannot be examined in detail in this module. The following are typical Energy Management Opportunities in the Retrofit category.

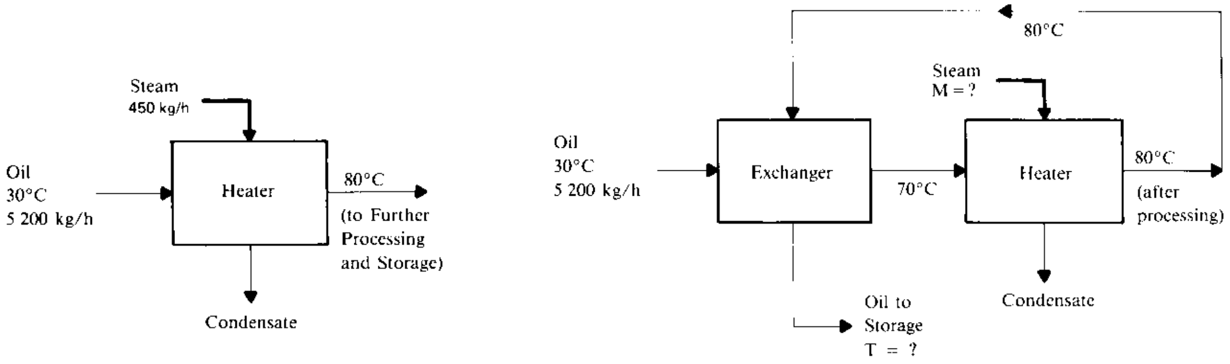
1. Use of heat exchangers to preheat a process stream.
2. Use of heat pipes to preheat make-up air for ovens.

Retrofit Worked Examples

1. **Heat Exchanger Installation**

A vegetable oil processing plant must heat partially processed oil to a specified temperature prior to the final refining steps. A steam heater is used.

The refined oil is sent to storage tanks at approximately that same temperature after processing. It is proposed that a heat exchanger can be installed to recover some of the heat from the oil being transferred to storage to preheat oil entering the steam heater. Steam requirements would thus be reduced. Figure 30 illustrates the existing and proposed systems.



Existing System

Proposed System

Vegetable Oil
Heat Exchanger Installation
Figure 30

As was discussed in the Fundamentals Section, it is not possible to transfer all of the heat from the warm to the cool oil. In practice, the exchanger size is selected to provide an acceptable return on investment based on the value of energy savings, the cost of the exchanger, and the cost of pumping oil through the exchanger and the piping.

An approach temperature of 10°C is reasonable in light of above discussion. This means that the temperature of the warmed up oil coming out of the heat exchanger is 70°C (i.e. 80°C - 10°C).

a) Heat transferred from the hot oil to the incoming oil can be calculated using the equation for sensible heat transfer as discussed in the Fundamentals Section. That is:

$$Q = M \text{ x } cp \text{ x } DT$$

$$= 5{,}200 \text{ kg/hr x } 2.09 \text{ kJ/kg}\cdot{}^\circ\text{C x } (70\text{-}30)^\circ\text{C}$$

$$= 43.5 \text{ x } 10^4 \text{ kJ/h}$$

Temperature of the oil going to storage is also found by:

$$Q = M \text{ x } cp \text{ x } DT$$

$$Q = M \text{ x } cp \text{ x } (T_{in} - T_{out})$$

or by rearranging the equation

$$T_{out} = T_{in} - \frac{Q}{Mcp}$$

$$= 80^\circ - \frac{43.5\text{x}10^4 \text{ kJ/h}}{5{,}200 \text{ kg/h x } 2.09 \text{ kJ/kg}\cdot{}^\circ\text{C}}$$

$$T_{out} = 40^\circ\text{C}$$

b) Steam required to heat oil from 30°C to 80°C (i.e. present system)

Heat Transferred to Oil

$$Q = M \text{ x } cp \text{ x } DT$$

$$= 5{,}200 \text{ kg/h x } 2.09 \text{ kJ/kg}\cdot{}^\circ\text{C x } (80 - 30)^\circ\text{C}$$

$$= 54.3 \text{ x } 10^4 \text{ kJ/h}$$

Quantity of steam required (steam)

$$Q = h_{fg} \text{ x } M$$

$$\text{or } M = \frac{Q}{h_{fg}}$$

Where: h_{fg} is the enthalpy of dry, saturated steam at atmospheric pressure

$$M = \frac{54.3 \text{ x } 10^4 \text{ kJ/h}}{2257 \text{ kJ/kg}}$$

$$= 240.8 \text{ kg/h}$$

c) Steam required to heat oil from 70°C to 80°C (i.e., proposed system)

Heat transfer to oil

$Q = M \times cp \times DT$

$= 5{,}200 \text{ kg/h} \times 2.09 \text{ kJ/kg}\cdot°\text{C} \times (80\text{-}70)°\text{C}$

$= 10.9 \times 10^4 \text{ kJ/h}$

Quantity of steam required

$Q = h_{fg} \times M$

or $M = \dfrac{Q}{h_{fg}}$

Where h_{fg} is the enthalpy of dry, saturated steam at atmospheric pressure.

$$M = \frac{10.9 \times 10^4 \text{ kg/h}}{2257 \text{ kJ/kg}}$$

$= 48.2 \text{ kg/h}$

d) Net Savings in Steam

Steam Savings = (240-48) kg/h

= 192 kg/h

(e) Calculation of Natural Gas Cost Savings:

If natural gas costs \$4.27/GJ (\$4.50/mcf) and is combusted at 60 percent efficiency, then the savings in natural gas costs equates to:

$$= Q \times h_{fg} \times \frac{1}{E_{boiler}} \times \frac{\$}{\text{Unit Energy Content of Fuel}}$$

$$= 192 \text{ kg/n} \times 2257 \text{ kJ/kg} \times \frac{1}{.6} \times \frac{\$4.27}{\text{GJ}}$$

= \$3.08/h

or on a yearly basis, based on 8 h/day
5 day/wk
240 day/year

Savings = \$29,570

f) Calculation of Simple Payback

Cost of the exchanger was determined to be \$19,000 (installed).

$$\text{Simple Payback} = \frac{\$19{,}000}{\$29{,}570}$$

= .64 years

2. Heat Pipe Installation

A manufacturer has an oven which presently exhausts 3,330 L/s of air at 130°C. A heat pipe installation is being considered to recover heat from the exhaust stream and use it to preheat the make-up air for the oven. Natural gas requirements would be reduced accordingly.

Other operating conditions include:

— operating hours	3800 hours/year
— average outdoor temperature	5°C
— make-up air volume	1915 L/s
— heat pipe efficiency	60%

a) Calculation of energy the heat pipe will recover from the Waste Heat

The equation used is basically that presented in the Fundamentals Section on calculation of sensible heat transfer:

$$Q = M \text{ x } cp \text{ x } DT$$

Slight modification is required however to convert the volume of air to a weight basis and to account for efficiency of the heat pipe (i.e. 60%).

$$Q = (1915 \text{ L/s x } 1.197 \text{ x } 10^{-3} \text{ kg/L}) \text{ x } (1.006 \text{ kJ/kg}\cdot{}^{\circ}\text{C}) \text{ x } (130^{\circ}\text{-}5)^{\circ}\text{C x } (.6)$$

$$= 173 \text{ kJ/s}$$

or on the basis of 3,800 hour/year operation.

$$Q = 2.37 \text{ x } 10^{9} \text{ kJ/yr}$$

b) Calculation of Natural Gas Cost Savings:

If natural gas costs $4.27/GJ ($4.50/mcf) and is combusted at 90 percent efficiency, then the savings in natural gas costs equates to:

$$= Q \text{ x } \frac{1}{E_{oven}} \text{ x } \frac{\$}{\text{Unit Energy Content of Fuel}}$$

$$= 2.77 \text{ x } 10^{9} \text{ kJ/yr x } \frac{1}{.9} \text{ x } \frac{\$4.27}{\text{GJ}}$$

$$= \$11,240$$

c) Calculation of Simple Payback

The cost of the heat pipe system (installed) was determined to be $16,000. Annual operating costs are $750.

$$\text{Simple payback} = \frac{\$16,000}{\$11,240 - \$750}$$

$$= 1.52 \text{ yrs}$$

APPENDICES

- A Glossary of Terms
- B Tables
- C Common Conversions

Glossary

Absolute Pressure — Any pressure where the base for measurement is full vacuum (i.e. gauge pressure and atmospheric pressure). Expressed in kPa (absolute).

Approach Temperature — In a heat exchanger, the difference in temperature between the treated fluid leaving and the working fluid entering the exchanger. In an evaporative cooling device, the difference between the average temperature of the circulating water leaving and the average wet bulb temperature of the air leaving the device.

ASHRAE — The American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Audit, diagnostic — The analysis of a potential opportunity to save energy which could involve the assessment of the current process operation and records, and the calculation of savings, of capital and operating costs so that the financial viability of the project can be established.

Audit, walk through — The visual inspection of a facility to observe how energy is used or wasted.

Clearance Volume — The space in a cylinder not occupied by the piston at the end of the compression stroke, measured in percent of piston displacement.

Compression Ratio — The ratio of discharge pressure to suction pressure of a compressor expressed in absolute units.

Condenser — A heat exchanger in which the refrigerant, after having been compressed to a suitable pressure, is condensed by rejection of heat to an external cooling medium.

Condensation — The process of changing a vapor into liquid by the extraction of heat.

Cooling Water — Water used for cooling a process or condenser.

Cycle closed — Any cycle in which the primary medium is always enclosed and repeats the same sequence of events.

Degree Kelvin — A unit of temperature measurement where zero Kelvin (0 K) is absolute to zero and is equal to -273°C. The K and °C are equal increments of temperature.

Dew Point — The temperature at which a vapor condenses when it is cooled at constant pressure.

Ejector, steam — A nozzle-like device that builds up a high fluid velocity in a restricted area to obtain a lower static pressure at that point so that fluid from another source can be drawn in.

Energy — The capacity for doing work; taking a number of forms that may be transformed from one into another, such as thermal (heat), mechanical (work), electrical, and chemical; in customary units, measured in kilowatt hours (kWh) or megajoules (MJ).

Energy Efficiency Ratio (EER) — A measure of efficiency of a refrigeration or heat pump system which compares the actual refrigeration effect to the actual work or energy input to the cycle. (Note: This ratio exists only in the Imperial Form Measurement.)

Energy Management Opportunities (EMO), housekeeping — Potential energy saving activities which should be done on a regular basis and never less than once per year. This includes preventive maintenance programs.

Energy Management Opportunities (EMO), low cost — Potential energy saving improvements that are done once and for which the cost is not considered great.

Energy Management Opportunities (EMO), retrofit — Potential energy saving improvements that are done once and for which the cost is significant.

Energy, waste — Energy which is lost without being fully utilized. It may include energy in a fluid or stream such as steam, exhaust gas, discharge water or even refuse.

Enthalpy — Enthalpy is a measure of the heat energy per unit mass of a material. Units are expressed as kJ/kg.

Entropy — The ratio of the heat added to a substance to the absolute temperature at which it was added; a measure of the molecular disorder of a substance at a given state.

Evaporator — A heat exchanger in which the liquid refrigerant, is evaporated by absorption of heat from the medium to be cooled.

Flash Chamber — A separating tank placed between the expansion valve and the evaporator to separate and bypass any flash gas formed in the expansion valve.

Flash Gas — The gas resulting from the instantaneous evaporation of a liquid when the pressure above the liquid is reduced. The remaining liquid is thereby cooled. Generation of flash gas occurs at the throttling device in a refrigeration process when the pressure above the liquid is reduced to below the saturation pressure of the liquid at a given temperature.

Fusion — Melting of a substance.

Gas, dry saturated — Vapor containing no liquid, whose quality is one (1); and whose state can be graphically defined as being on the saturation line of a state diagram, to the right of the critical point.

Gas, hot — The vapor discharged from the compressor in a vapor compression cycle — the gas is "hot" as compared to the suction gas due to the addition of energy in the form of work of compression.

Gas, suction — The refrigerant vapor on the suction side of a compressor in a vapor compression cycle; the evaporator coil discharge gas.

Heat Exchanger — A device specifically designed to transfer heat between two physically separated fluids.

Heat Sink — The medium or device to which heat is rejected; must always be at a lower temperature than that of the medium rejecting heat for heat transfer to occur. For example a condenser rejects heat to a lake through a heat exchanger — the lake acts as a heat sink.

Heat Source — A medium or process from which heat may be extracted; must always be at a temperature higher than the medium or process requiring the heat for heat transfer to occur; see waste heat. For example, flash steam from a boiler plant might be used as heat source for regenerating the refrigerant from the solvent in an absorption chiller.

Heat, waste — Energy in the form of heat rejected or lost from a process, which may be recovered or reused in another process providing it is of sufficient quality (i.e., hot enough and there is a use for it).

Insulation — A material of low thermal conductivity used to reduce the passage of heat.

Latent Heat — The heat which causes change in phase. The change of enthalpy during a change of state; the amount of heat absorbed or rejected at constant temperature at any pressure; or the difference in enthalpies of a pure condensable fluid between its dry saturated state and its saturated liquid state at the same pressure.

Pressure, differential — The difference in pressure between two points.

Pressure, gauge — Any pressure where the base for measurement is atmospheric pressure expressed as kPa (gauge). Note: that kPa (gauge) + atmospheric pressure = kPa (absolute).

Process — A change in the properties of a system or substance, usually defined by the conditions at the start and at the end of the process.

Property — A physical characteristic of a substance used to describe its state. Any two properties will usually define the state or condition of the substance from which all other properties can be derived. Examples are temperature, pressure, enthalpy and entropy.

Recuperator — A heat exchanger designed to recover what otherwise would be waste heat.

Refrigerating Capacity — The net or nominal cooling or heating capacity of a given refrigeration system, expressed in watts or kilowatts cooling.

Refrigeration Effect — The net quantity of cooling or heat rejection obtained, not including spurious effects such as heat gains from piping or the heat added to the refrigerant vapor at the compressor.

Saturation Pressure — The pressure of a liquid or vapor at saturation conditions (i.e., on or under the saturation curve).

Saturation Temperature — The temperature of a liquid or vapor at saturation conditions (i.e., on or under the saturation curve).

Specific Volume — The volume per unit of a substance, usually expressed in cubic metres per kilogram (m^3/kg); the inverse of specific density.

State — The state of a system or substance is the condition of the system or substance characterized by the values of its properties such as temperature and pressure. The term is often used interchangeably with the term "phase", as in the solid phase or gaseous phase of a substance.

Thermal Resistance — A number indicating the insulating value or resistance to heat flow of a material or assembly.

Throttling of a Fluid — A process which consists of lowering pressure by expansion without work or heat input.

Vapor — A gas at or near equilibrium with the liquid phase; a gas under the saturation curve or only slightly beyond the saturated vapor line.

Water, condenser — Cool water circulated through a condenser to condense a refrigerant or vapor.

Work — Mechanical energy imparted in a process or to a substance.

Zero, Absolute — The theoretical temperature at which all molecular motion stops, defined as -273°Celsius or, 0 Kelvin.

PROPERTIES OF SATURATED STEAM AND SATURATED WATER (TEMPERATURE)

TABLE 1

Temperature		Press.	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/kg K		
°C	K	kPa	Water	Evap.	Steam	Water	Evap.	Steam	Water	Evap.	Steam
t	T	p	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
0.	273.15	0.6108	0.0010002	206,30	206,31	-0,04	2501,6	2501,6	-0,0002	9,1579	9,1577
0.01	273.16	0.6112	0.0010002	206,16	206,16	0,00	2501,6	2501,6	0,0000	9,1575	9,1575
1.0	274.15	0.6566	0.0010001	192,61	192,61	4,17	2499,2	2503,4	0,0153	9,1158	9,1311
2.0	275.15	0.7055	0.0010001	179,92	179,92	8,39	2496,8	2505,2	0,0306	9,0741	9,1047
3.0	276.15	0,7575	0.0010001	168,17	168,17	12,60	2494,5	2507,1	0,0459	9,0326	9,0785
4.0	277.15	0.8129	0.0010000	157,27	157,27	16,80	2492,1	2508,9	0,0611	8,9915	9,0526
5.0	278.15	0,8718	0.0010000	147,16	147,16	21,01	2489,7	2510,7	0,0762	8,9507	9,0269
6.0	279.15	0,9345	0.0010000	137,78	137,78	25,21	2487,4	2512,6	0,0913	8,9102	9,0015
7.0	280.15	1,0012	0.0010001	129,06	129.06	29,41	2485,0	2514,4	0,1063	8,8699	8,9762
8.0	281.15	1.0720	0.0010001	120,96	120,97	33,60	2482,6	2516,2	0,1213	8,8300	8,9513
9.0	282.15	1.1472	0.0010002	113.43	113,44	37,80	2480,3	2518,1	0,1362	8.7903	8,9265
10.0	283.15	1.2270	0.0010003	106.43	106,43	41,99	2477,9	2519.9	0.1510	8,7510	8,9020
12.0	285.15	1,4014	0.0010004	93.83	93.84	50,38	2473,2	2523,6	0,1805	8,6731	8,8536
14.0	287.15	1,5973	0.0010007	82.90	82,90	58,75	2468,5	2527,2	0,2098	8,5963	8,8060
16.0	289.15	1,8168	0,0010010	73,38	73,38	67,13	2463,8	2530,9	0,2388	8,5205	8,7593
18.0	291.15	2,0624	0.0010013	65.09	65,09	75,50	2459,0	2534,5	0.2677	8,4458	8,7135
20.0	293.15	2.337	0.0010017	57,84	57,84	83,86	2454,3	2538,2	0,2963	8,3721	8.6694
22.0	295.15	2.642	0.0010022	51,49	51,49	92,23	2449,6	2541,8	0,3247	8,2994	8.6241
24.0	297.15	2,982	0.0010026	45,92	45,93	100,59	2444,9	2545,5	0,3530	8.2277	8,5806
26.0	299.15	3.360	0.0010032	41.03	41,03	108,95	2440,2	2549,1	0,3810	8.1569	8,5379
28.0	301.15	3.778	0.0010037	36,73	36,73	117,31	2435,4	2552.7	0.4088	8,0870	8,4959
30.0	303.15	4.241	0.0010043	32,93	32,93	125.66	2430,7	2556.4	0,4365	8,0181	8,4546
32.0	305.15	4.753	0.0010049	29.57	29,57	134.02	2425,9	2560,0	0,4640	7,9500	8.4140
34.0	307.15	5.318	0.0010056	26.60	26,60	142,34	2421,2	2563,6	0,4913	7.8828	8,3740
36.0	309.15	5.940	0.0010063	23,97	23,97	150.74	2416,4	2567,2	0,5184	7,8164	8,3348
38.0	311.15	6,624	0.0010070	21.63	21.63	159,09	2411,7	2570,8	0,5453	7,7509	8,2962
40.0	313.15	7.375	0.0010078	19,545	19.546	167,45	2406,9	2574,4	0,5721	7.6861	8,2583
42.0	315.15	8.198	0.0010086	17,691	17.692	175,81	2402,1	2577,9	0,5987	7,6222	8.2209
44.0	317.15	9.100	0.0010094	16,035	16.036	184,17	2397,3	2581,5	0,6252	7.5590	8,1842
46.0	319.15	10.086	0.0010103	14,556	14.557	192,53	2392.5	2585,1	0,6514	7,4966	8.1481
48.0	321.15	11.162	0.0010112	13,232	13.233	200.89	2387,7	2588,6	0.6776	7,4350	8.1125
50.0	323.15	12.335	0.0010121	12,045	12.046	209,26	2382,9	2592,2	0,7035	7,3741	8,0776
52.0	325.15	13.613	0.0010131	10,979	10.980	217,62	2378,1	2595,7	0,7293	7,3138	8,0432
54.0	327.15	15.002	0.0010140	10,021	10,022	225.99	2373,2	2599,2	0,7550	7.2543	8,0093
56.0	329.15	16.511	0.0010150	9,158	9.159	234,35	2368,4	2602,7	0,7804	7,1955	7,9759
58.0	331.15	18.147	0.0010161	8,380	8,381	242,72	2363,5	2606,2	0,8058	7,1373	7,9431
60.0	333.15	19.920	0.0010171	7,678	7.679	251,09	2358,6	2609,7	0,8310	7,0798	7,9108
62.0	335.15	21.838	0,0010182	7,043	7.044	259,46	2353,7	2613,2	0,8560	7,0230	7,8790
64.0	337.15	23,912	0.0010193	6,468	6.469	267.84	2348,8	2616,6	0,8809	6,9667	7,8477
66.0	339.15	26.150	0.0010205	5,947	5,948	276.21	2343,9	2620.1	0,9057	6,9111	7,8168
68.0	341.15	28.563	0.0010217	5.475	5.476	284,59	2338,9	2623,5	0,9303	6,8561	7.7864
70.0	343.15	31.16	0.0010228	5,045	5,046	292,97	2334,0	2626,9	0,9548	6,8017	7,7565
72.0	345.15	33,96	0.0010241	4,655	4,656	301.36	2329,0	2630,3	0,9792	6,7478	7,7270
74.0	347.15	36,96	0.0010253	4.299	4.300	309,74	2324,0	2633,7	1,0034	6,6945	7,6979
76.0	349.15	40.19	0.0010266	3,975	3,976	318,13	2318,9	2637.1	1,0275	6,6418	7,6693
78.0	351.15	43,65	0.0010279	3,679	3.680	326,52	2313,9	2640.4	1,0514	6,5896	7.6410
80.0	353.15	47.36	0.0010292	3.408	3.409	334.92	2308.8	2643.8	1.0753	6,5380	7.6132
82.0	355.15	51.33	0.0010305	3,161	3.162	343.31	2303,8	2647,1	1,0990	6,4868	7,5858
84.0	357.15	55.57	0.0010319	2,934	2,935	351.71	2298,6	2650,4	1.1225	6,4362	7,5588
86.0	359.15	60.11	0.0010333	2,726	2,727	360,12	2293,5	2653,6	1,1460	6,3861	7,5321
88.0	361.15	64,95	0.0010347	2,535	2.536	368,53	2288,4	2656.9	1,1693	6,3365	7,5058
90.0	363.15	70.11	0.0010361	2,3603	2.3613	376.94	2283,2	2660,1	1.1925	6,2873	7,4799
92.0	365.15	75,61	0.0010376	2,1992	2,2002	385,36	2278,0	2663,4	1,2156	6,2387	7,4543
94.0	367.15	81,46	0.0010391	2.0509	2,0519	393,78	2272,9	2666,6	1.2386	6,1905	7,4291
96.0	369.15	87.69	0.0010406	1,9143	1,9153	402,20	2267,5	2669,7	1.2615	6,1427	7,4042
98.0	371.15	94,30	0.0010421	1.7883	1,7893	410.63	2262,2	2672,9	1,2842	6,0954	7,3796
100.0	373.15	101.33	0.0010437	1.6720	1.6730	419,06	2256,9	2676,0	1,3069	6,0485	7,3554

PROPERTIES OF SATURATED STEAM AND SATURATED WATER (TEMPERATURE)

TABLE 1

Temperature		Press.	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/kg K		
°C	K	kPa	Water	Evap.	Steam	Water	Evap.	Steam	Water	Evap.	Steam
t	T	p	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
100.0	373.15	101.33	0.0010437	1,6720	1,6730	419,06	2256,9	2676,0	1,3069	6,0485	7,3554
105.0	378.15	120.80	0.0010477	1,4182	1,4193	440,17	2243,6	2683,7	1,3630	5,9331	7,2962
110.0	383.15	143.27	0.0010519	1,2089	1,2099	461.32	2230.0	2691,3	1,4185	5,8203	7.2388
115.0	388.15	169.06	0.0010562	1,0352	1.0363	482,50	2216.2	2698,7	1,4733	5.7099	7,1832
120.0	393.15	198,54	0.0010606	0,8905	0,8915	503,72	2202.2	2706,0	1,5276	5,6017	7.1293
125.0	398.15	232,1	0.0010652	0.7692	0.7702	524,99	2188.0	2713.0	1,5813	5,4957	7.0769
130.0	403.15	270.1	0,0010700	0,6671	0,6681	546,31	2173,6	2719,9	1,6344	5,3917	7,0261
135.0	408.15	313,1	0.0010750	0,5807	0,5818	567,68	2158,9	2726,6	1,6869	5,2897	6,9766
140.0	413.15	361,4	0.0010801	0,5074	0,5085	589,10	2144,0	2733,1	1,7390	5.1894	6,9284
145.0	418.15	415,5	0.0010853	0,4449	0,4460	610,59	2128,7	2739,3	1,7906	5.0910	6.8815
150.0	423.15	476.0	0.0010908	0.3914	0,3924	632,15	2113.2	2745,4	1,8416	4.9941	6.8358
155.0	428.15	543,3	0.0010964	0,3453	0,3464	653,77	2097,4	2751,2	1,8923	4.8989	6,7911
160.0	433.15	618.1	0.0011022	0,3057	0,3068	675,47	2081,3	2756,7	1,9425	4,8050	6.7475
165.0	438.15	700.8	0.0011082	0,2713	0,2724	697,25	2064,8	2762,0	1,9923	4.7126	6.7048
170.0	443.15	792.0	0.0011145	0,2414	0,2426	719.12	2047,9	2767,1	2,0416	4,6214	6.6630
175.0	448.15	892,4	0.0011209	0,21542	0,21654	741,07	2030,7	2771,8	2,0906	4,5314	6,6221
180.0	453.15	1002,7	0.0011275	0,19267	0,19380	763,12	2013.2	2776,3	2,1393	4,4426	6.5819
185.0	458.15	1123.3	0.0011344	0.17272	0,17386	785,26	1995.2	2780,4	2,1876	4.3548	6.5424
190.0	463.15	1255.1	0.0011415	0.15517	0,15632	807,52	1976,7	2784,3	2,2356	4,2680	6,5036
195.0	468.15	1398.7	0.0011489	0.13969	0,14084	829,88	1957.9	2787,8	2,2833	4,1821	6.4654
200.0	473.15	1554.9	0.0011565	0.12600	0,12716	852,37	1938,6	2790,9	2,3307	4,0971	6.4278
205.0	478.15	1724,3	0.0011644	0.11386	0.11503	874,99	1918.8	2793,8	2,3778	4.0128	6.3906
210.0	483.15	1907,7	0.0011726	0.10307	0,10424	897,73	1898.5	2796,2	2,4247	3.9293	6.3539
215.0	488.15	2106,0	0.0011811	0,09344	0,09463	920,63	1877,6	2798,3	2,4713	3,8463	6.3176
220.0	493.15	2319,8	0.0011900	0,08485	0,08604	943,67	1856.2	2799,9	2,5178	3.7639	6.2817
225.0	498.15	2550,	0.0011992	0.07715	0.07835	966,88	1834,3	2801.2	2,5641	3,6820	6.2461
230.0	503.15	2798,	0.0012087	0,07024	0,07149	990,27	1811.7	2802,0	2,6102	3,6006	6.2107
235.0	508.15	3063,	0.0012187	0,06403	0,06525	1013,83	1788,5	2802,3	2,6561	3,5194	6.1756
240.0	513.15	3348,	0.0012291	0,05843	0,05965	1037,60	1764,6	2802,2	2,7020	3.4386	6.1406
245.0	518.15	3652,	0.0012399	0,05337	0.05461	1061,58	1740.0	2801,6	2,7478	3.3579	6.1057
250.0	523.15	3978,	0.0012513	0,04879	0,05004	1085,78	1714,7	2800.4	2,7935	3.2773	6.0708
255.0	528.15	4325.	0.0012632	0,04463	0,04590	1110,23	1688,5	2798,7	2,8392	3.1968	6.0359
260.0	533.15	4694.	0.0012756	0,04086	0,04213	1134,94	1661.5	2796,4	2,8848	3,1161	6.0010
265.0	538.15	5088.	0.0012887	0,03742	0,03871	1159,93	1633,5	2793,5	2,9306	3,0353	5.9658
270.0	543.15	5506.	0.0013025	0,03429	0.03559	1185.23	1604,6	2789,9	2,9763	2.9541	5.9304
275.0	548.15	5950.	0.0013170	0.03142	0,03274	1210,86	1574,7	2785,5	3,0722	2,8725	5.8947
280.0	553.15	6420.	0.0013324	0,02879	0,03013	1236,84	1543,6	2780,4	3,0683	2.7903	5,8586
285.0	558.15	6919,	0.0013487	0,02638	0,02773	1263,21	1511.3	2774,5	3,1146	2.7074	5.8220
290.0	563.15	7446,	0.0013659	0.02417	0,02554	1290,01	1477.6	2767,6	3,1611	2.6237	5.7848
295.0	568.15	8004,	0.0013844	0,02213	0.02351	1317,27	1442.6	2759,8	3,2079	2.5389	5.7469
300.0	573.15	8593,	0.0014041	0,020245	0,021649	1345,05	1406.0	2751,0	3,2552	2,4529	5.7081
305.0	578.15	9214,	0.0014252	0,018502	0,019927	1373,40	1367,7	2741,1	3,3029	2,3656	5,6685
310.0	583.15	9870,	0.0014480	0,016886	0,018334	1402,39	1327,6	2730,0	3,3512	2.2766	5,6278
315.0	588.15	10561,	0.0014726	0,015383	0,016856	1432,09	1285,5	2717,6	3,4002	2.1856	5.5858
320.0	593.15	11289,	0.0014995	0,013980	0,015480	1462,60	1241,1	2703,7	3,4500	2,0923	5,5423
325.0	598.15	12056,	0.0015289	0,012666	0,014195	1494,03	1194,0	2688,0	3,5408	1.9961	5,4969
330.0	603.15	12863,	0.0015615	0,011428	0,012989	1526,52	1143,6	2670.2	3,5528	1.8962	5.4490
335.0	608.15	13712,	0.0015978	0,010256	0,011854	1560,25	1089.5	2649,7	3.6063	1.7916	5.3979
340.0	613.15	14605,	0.0016387	0,009142	0,010780	1595,47	1030.7	2626,2	3,6616	1,6811	5,3427
345.0	618.15	15545,	0.0016858	0,008077	0,009763	1632,52	966,4	2596,9	3,7193	1,5636	5,2828
350.0	623.15	16535,	0.0017411	0,007058	0,008799	1671,94	895,7	2567,7	3,7800	1.4376	5.2177
355.0	628.15	17577,	0.0018085	0,006051	0,007859	1716,63	813,8	2530,4	3,8489	1.2953	5.1442
360.0	633.15	18675,	0.0018959	0,005044	0,006940	1764,17	721.3	2485,4	3,9710	1.1390	5.0600
365.0	638.15	19833,	0.0020160	0,003996	0,006012	1817,96	610.0	2428,0	4,0021	0.9558	4.9579
370.0	643.15	21054.	0.0022136	0,002759	0.004973	1890,21	452,6	2342,6	4,1108	0,7036	4.8144
371.0	644.15	21306.	0.0022778	0,002446	0,004723	1910,50	407,4	2317,9	4,1414	0.6324	4.7738
372.0	645.15	21562,	0.0023636	0,002075	0,004439	1935,57	351,4	2287,0	4,1794	0,5446	4.7240
373.0	646.15	21820.	0.0024963	0,001588	0,004084	1970,50	273.5	2244,0	4,2326	0.4233	4.6559
374.0	647.15	22081.	0.0028427	0,000623	0,003466	2046,72	109.5	2156,2	4,3493	0.1692	4.5185
374.15	647.30	22120.	0.00317	0,0	0,00317	2107,37	0.0	2107,4	4,4429	0.0	4,4429

PROPERTIES OF SATURATED STEAM AND SATURATED WATER (PRESSURE)

TABLE 1

Press.	Temp.	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/kg K			Energy, kJ/kg	
kPa	°C	Water	Evap.	Steam	Water	Evap.	Steam	Water	Evap.	Steam	Water	Steam
p	t	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	u_f	u_g
1.0	6.983	0.0010001	129.21	129.21	29.34	2485.0	2514,4	0,1060	8,8706	8,9767	29.33	2385,2
1.1	8.380	0,0010001	118.04	118,04	35,20	2481,7	2516,9	0,1269	8,8149	8,9418	35.20	2387,1
1.2	9.668	0.0010002	108.70	108,70	40.60	2478,7	2519,3	0,1461	8,7640	8,9101	40.60	2388,9
1.3	10.866	0.0010003	100.76	100,76	45.62	2475,9	2521.5	0,1638	8,7171	8,8809	45.62	2390,5
1.4	11.985	0.0010004	93.92	93,92	50.31	2473,2	2523,5	0,1803	8,6737	8,8539	50.31	2392.0
1.5	13.036	0.0010006	87.98	87,98	54,71	2470.7	2525,5	0.1957	8,6332	8,8288	54.71	2393,5
1.6	14.026	0.0010007	82.76	82,77	58,86	2468.4	2527,3	0,2101	8,5952	8,8054	58.86	2394,8
1.8	15.855	0.0010010	74.03	74,03	66.52	2464,1	2530,6	0,2367	8,5260	8,7627	66.52	2397,4
2.0	17.513	0.0010012	67.01	67,01	73.46	2460,2	2533,6	0,2607	8,4639	8,7246	73.46	2399,6
2.2	19.031	0.0010015	61.23	61,23	79.81	2456,6	2536,4	0,2825	8,4077	8,6901	79.81	2401,7
2.4	20.433	0.0010019	56.39	56,39	85,67	2453.3	2539.0	0,3025	8,3563	8,6587	85.67	2403,6
2.6	21.737	0.0010021	52.28	52,28	91.12	2450,2	2541,3	0,3210	8,3089	8,6299	91.12	2405.4
2.8	22.955	0.0010024	48.74	48.74	96.22	2447,3	2543,6	0,3382	8,2650	8,6033	96.21	2407,1
3.0	24.100	0.0010027	45,67	45,67	101.00	2444,6	2545,6	0,3544	8,2241	8,5785	101.00	2408,6
3.5	26.694	0.0010033	39.48	39,48	111.85	2438.5	2550,4	0,3907	8,1325	8,5232	111.84	2412,2
4.0	28.983	0.0010040	34.80	34,80	121.41	2433,1	2554,5	0,4225	8,0530	8,4755	121.41	2415,3
4.5	31.035	0.0010046	31.14	31,14	129.99	2428,2	2558,2	0,4507	7,9827	8,4335	129.98	2418,1
5.0	32.898	0.0010052	28.19	28,19	137,77	2423,8	2561,6	0,4763	7,9197	8,3960	137.77	2420,6
5.5	34.605	0.0010058	25.77	25,77	144.91	2419,8	2564,7	0,4995	7,8626	8,3621	144.90	2422,9
6.0	36.183	0.0010064	23.74	23,74	151.50	2416,0	2567,5	0,5209	7,8104	8,3312	151.50	2425,1
6.5	37.651	0.0010069	22.015	22,016	157,64	2412.5	2570.2	0,5407	7,7622	8.3029	157.63	2427.0
7.0	39.025	0.0010074	20.530	20.531	163.38	2409.2	2572.6	0,5591	7,7176	8,2767	163.37	2428,9
7.5	40.316	0.0010079	19.238	19,239	168,77	2406,2	2574,9	0,5763	7,6760	8,2523	168.76	2430,6
8.0	41.534	0.0010084	18.104	18,105	173.86	2403,2	2577,1	0,5925	7,6370	8,2296	173.86	2432.3
9.0	43.787	0,0010094	16.203	16,204	183,28	2397,9	2581,1	0,6224	7,5657	8,1881	183.27	2435,3
10.	45.833	0.0010102	14.674	14,675	191.83	2392,9	2584,8	0,6493	7,5018	8,1511	191.82	2438.0
11.	47.710	0,0010111	13.415	13.416	199,68	2388,4	2588,1	0,6738	7,4439	8,1177	199.67	2440,5
12.	49.446	0.0010119	12.361	12,362	206.94	2384,3	2591,2	0,6963	7,3909	8,0872	206.93	2442,8
13.	51.062	0.0010126	11.465	11.466	213.70	2380.3	2594,0	0,7172	7,3420	8,0592	213.68	2445,0
14.	52.574	0.0010133	10.693	10,694	220.02	2376,7	2596,7	0,7367	7.2967	8,0334	220.01	2447,0
15.	53.997	0,0010140	10.022	10,023	225.97	2373.2	2599,2	0,7549	7,2544	8,0093	225.96	2448,9
16.	55.341	0,0010147	9.432	9.433	231.59	2370,0	2601.6	0,7721	7.2148	7,9869	231.58	2450,6
18.	57.826	0,0010160	8.444	8,445	241.99	2363.9	2605,9	0,8036	7,1424	7,9460	241.98	2453,9
20.	60.086	0.0010172	7.649	7,650	251.45	2358,4	2609,9	0,8321	7,0774	7,9094	251.43	2456,9
22.	62.162	0.0010183	6,994	6,995	260.14	2353,3	2613,5	0,8581	7,0184	7,8764	260.12	2459,6
24.	64,082	0,0010194	6.446	6,447	268.18	2348,6	2616.8	0,8820	6,9644	7,8464	268.16	2462,1
26.	65,871	0,0010204	5,979	5,980	275.67	2344,2	2619,9	0,9041	6,9147	7,8188	275.65	2464,4
28.	67,547	0.0010214	5.578	5,579	282.69	2340,0	2622,7	0,9248	6,8685	7,7933	282.66	2466,5
30.	69,124	0.0010223	5.228	5,229	289.30	2336,1	2625,4	0,9441	6,8254	7,7695	289.27	2468,6
35.	72.709	0.0010245	4.525	4,526	304.33	2327.2	2631,5	0,9878	6,7288	7,7166	304.29	2473,1
40.	75.886	0.0010265	3.992	3,993	317.65	2319.2	2636,9	1,0261	6,6448	7,6709	317.61	2477.1
45.	78.743	0.0010284	3.575	3,576	329.64	2312.0	2641.7	1,0603	6,5704	7,6307	329.59	2480,7
50.	81.345	0,0010301	3.239	3,240	340.56	2305,4	2646.0	1,0912	6,5035	7,5947	340.51	2484,0
55.	83.737	0.0010317	2.963	2,964	350.61	2299.3	2649,9	1,1194	6,4428	7,5623	350,56	2486,9
60.	85,954	0.0010333	2.731	2,732	359.93	2293,6	2653,6	1,1454	6,3873	7,5327	359,86	2489,7
65.	88,021	0,0010347	2.5335	2,5346	368,62	2288,3	2656,9	1,1696	6,3360	7,5055	368.55	2492,2
70.	89.959	0.0010361	2.3637	2,3647	376,77	2283,3	2660,1	1,1921	6,2883	7,4804	376.70	2494,5
75.	91.785	0.0010375	2.2158	2,2169	384,45	2278,6	2663,0	1,2131	6,2439	7,4570	384.37	2496,7
80.	93.512	0.0010387	2,0859	2,0870	391.72	2274,1	2665,8	1,2330	6,2022	7,4352	391.64	2498,8
90.	96.713	0,0010412	1.8682	1,8692	405.21	2265,6	2670,9	1,2696	6,1258	7,3954	405.11	2502,6
100.	99,632	0,0010434	1.6927	1,6937	417.51	2257,9	2675,4	1,3027	6,0571	7,3598	417.41	2506,1
110.	102.317	0,0010455	1,5482	1,5492	428,84	2250,8	2679,6	1,3330	5,9947	7,3277	428.73	2509,2
120.	104.808	0,0010476	1.4271	1,4281	439.36	2244,1	2683,4	1,3609	5,9375	7,2984	439.24	2512,1
130.	107,133	0.0010495	1.3240	1,3251	449,19	2237,8	2687.0	1,3868	5,8847	7,2715	449,05	2514,7
140.	109.315	0,0010513	1,2353	1,2363	458,42	2231,9	2690,3	1,4109	5,8356	7,2465	458,27	2517,2
150.	111.37	0,0010530	1.1580	1.1590	467,13	2226.2	2693,4	1,4336	5,7898	7,2234	466.97	2519,5
160.	113.32	0.0010547	1.0901	1,0911	475,38	2220.9	2696,2	1,4550	5,7467	7,2017	475.21	2521,7
180.	116.93	0.0010579	0.9762	0,9772	490.70	2210,8	2701,5	1,4944	5,6678	7,1622	490.51	2525,6
200.	120,23	0.0010608	0,8844	0,8854	504,70	2201.6	2706.3	1,5301	5,5967	7,1268	504,49	2529.2
220.	123.27	0.0010636	0.8088	0.8098	517,62	2193.0	2710.6	1,5627	5,5321	7,0949	517.39	2532,4
240.	126.09	0.0010663	0.7454	0,7465	529.63	2184,9	2714,5	1,5929	5,4728	7,0657	529.38	2535,4

PROPERTIES OF SATURATED STEAM AND SATURATED WATER (PRESSURE)

TABLE 1

Press.	Temp.	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/kg K			Energy, kJ/kg	
kPa	°C	Water	Evap.	Steam	Water	Evap.	Steam	Water	Evap.	Steam	Water	Steam
p	t	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	u_f	u_g
240.	126.09	0.0010663	0.7454	0.7465	529.6	2184.9	2714.5	1.5929	5.4728	7.0657	529.38	2535.4
260.	128.73	0.0010688	0.6914	0.6925	540.9	2177.3	2718.2	1.6209	5.4180	7.0389	540.60	2538.1
280.	131.20	0.0010712	0.6450	0.6460	551.4	2170.1	2721.5	1.6471	5.3670	7.0140	551.14	2540.6
300.	133.54	0.0010735	0.6045	0.6056	561.4	2163.2	2724.7	1.6716	5.3193	6.9909	561.11	2543.0
350.	138.87	0.0010789	0.5229	0.5240	584.3	2147.4	2731.6	1.7273	5.2119	6.9392	583.89	2548.2
400.	143.62	0.0010839	0.4611	0.4622	604.7	2133.0	2737.6	1.7764	5.1179	6.8943	604.24	2552.7
450.	147.92	0.0010885	0.4127	0.4138	623.2	2119.7	2742.9	1.8204	5.0343	6.8547	622.67	2556.7
500.	151.84	0.0010928	0.3736	0.3747	640.1	2107.4	2747.5	1.8604	4.9588	6.8192	639.57	2560.2
550.	155.47	0.0010969	0.3414	0.3425	655.8	2095.9	2751.7	1.8970	4.8900	6.7870	655.20	2563.3
600.	158.84	0.0011009	0.3144	0.3155	670.4	2085.0	2755.5	1.9308	4.8267	6.7575	669.76	2566.2
650.	161.98	0.0011046	0.29138	0.29249	684.1	2074.7	2758.9	1.9623	4.7681	6.7304	683.42	2568.7
700.	164.96	0.0011082	0.27157	0.27268	697.1	2064.9	2762.0	1.9918	4.7134	6.7052	696.29	2571.1
750.	167.76	0.0011116	0.25431	0.25543	709.3	2055.5	2764.8	2.0195	4.6621	6.6817	708.47	2573.3
800.	170.41	0.0011150	0.23914	0.24026	720.9	2046.5	2767.5	2.0457	4.6139	6.6596	720.04	2575.3
900.	175.36	0.0011213	0.21369	0.21481	742.6	2029.5	2772.1	2.0941	4.5250	6.6192	741.63	2578.8
1000.	179.88	0.0011274	0.19317	0.19429	762.6	2013.6	2776.2	2.1382	4.4446	6.5828	761.48	2581.9
1100.	184.07	0.0011331	0.17625	0.17738	781.1	1998.5	2779.7	2.1786	4.3711	6.5497	779.88	2584.5
1200.	187.96	0.0011386	0.16208	0.16320	798.4	1984.3	2782.7	2.2161	4.3033	6.5194	797.06	2586.9
1300.	191.61	0.0011438	0.14998	0.15113	814.7	1970.7	2785.4	2.2510	4.2403	6.4913	813.21	2589.0
1400.	195.04	0.0011489	0.13957	0.14072	830.1	1957.7	2787.8	2.2837	4.1814	6.4651	828.47	2590.8
1500.	198.29	0.0011539	0.13050	0.13166	844.7	1945.2	2789.9	2.3145	4.1261	6.4406	842.93	2592.4
1600.	201.37	0.0011586	0.12253	0.12369	858.6	1933.2	2791.7	2.3436	4.0739	6.4175	856.71	2593.8
1800.	207.11	0.0011678	0.10915	0.11032	884.6	1910.3	2794.8	2.3976	3.9775	6.3751	882.47	2596.3
2000.	212.37	0.0011766	0.09836	0.09954	908.6	1888.6	2797.2	2.4469	3.8898	6.3367	906.24	2598.2
2200.	217.24	0.0011850	0.08947	0.09065	931.0	1868.1	2799.1	2.4922	3.8093	6.3015	928.35	2599.6
2400.	221.78	0.0011932	0.08201	0.08320	951.9	1848.5	2800.4	2.5343	3.7347	6.2690	949.07	2600.7
2600.	226.04	0.0012011	0.07565	0.07686	971.7	1829.6	2801.4	2.5736	3.6651	6.2387	968.60	2601.5
2800.	230.05	0.0012088	0.07018	0.07139	990.5	1811.5	2802.0	2.6106	3.5998	6.2104	987.10	2602.1
3000.	233.84	0.0012163	0.06541	0.06663	1008.4	1793.9	2802.3	2.6455	3.5382	6.1837	1004.70	2602.4
3500.	242.54	0.0012345	0.05579	0.05703	1049.8	1752.2	2802.0	2.7253	3.3976	6.1228	1045.44	2602.4
4000.	250.33	0.0012521	0.04850	0.04975	1087.4	1712.9	2800.3	2.7965	3.2720	6.0685	1082.4	2601.3
4500.	257.41	0.0012691	0.04277	0.04404	1122.1	1675.6	2797.7	2.8612	3.1579	6.0191	1116.4	2599.9
5000.	263.91	0.0012858	0.03814	0.03943	1154.5	1639.7	2794.2	2.9206	3.0529	5.9735	1148.0	2597.0
5500.	269.93	0.0013023	0.03433	0.03563	1184.9	1605.0	2789.9	2.9757	2.9552	5.9309	1177.7	2594.0
6000.	275.55	0.0013187	0.03112	0.03244	1213.7	1571.3	2785.0	3.0273	2.8635	5.8908	1205.8	2590.4
6500.	280.82	0.0013350	0.028384	0.029719	1241.1	1538.4	2779.5	3.0759	2.7768	5.8527	1232.5	2586.3
7000.	285.79	0.0013513	0.026022	0.027373	1267.4	1506.0	2773.5	3.1219	2.6943	5.8162	1258.0	2581.8
7500.	290.50	0.0013677	0.023959	0.025327	1292.7	1474.2	2766.9	3.1657	2.6153	5.7811	1282.4	2577.0
8000.	294.97	0.0013842	0.022141	0.023525	1317.1	1442.8	2759.9	3.2076	2.5395	5.7471	1306.0	2571.7
9000.	303.31	0.0014179	0.019078	0.020495	1363.7	1380.9	2744.6	3.2867	2.3953	5.6820	1351.0	2560.1
10000.	310.96	0.0014526	0.016589	0.018041	1408.0	1319.7	2727.7	3.3605	2.2593	5.6198	1393.5	2547.3
11000.	318.05	0.0014887	0.014517	0.016006	1450.6	1258.7	2709.3	3.4304	2.1291	5.5595	1434.2	2533.2
12000.	324.65	0.0015268	0.012756	0.014283	1491.8	1197.4	2689.2	3.4972	2.0030	5.5002	1473.4	2517.8
13000.	330.83	0.0015672	0.011230	0.012797	1532.0	1135.0	2667.0	3.5616	1.8792	5.4408	1511.6	2500.6
14000.	336.64	0.0016106	0.009884	0.011495	1571.6	1070.7	2642.4	3.6242	1.7560	5.3803	1549.1	2481.4
15000.	342.13	0.0016579	0.008682	0.010340	1611.0	1004.0	2615.0	3.6859	1.6320	5.3178	1586.1	2459.9
16000.	347.33	0.0017103	0.007597	0.009308	1650.5	934.3	2584.9	3.7471	1.5060	5.2531	1623.2	2436.0
17000.	352.26	0.0017696	0.006601	0.008371	1691.7	859.9	2551.6	3.8107	1.3748	5.1855	1661.6	2409.3
18000.	356.96	0.0018399	0.005658	0.007498	1734.8	779.1	2513.9	3.8765	1.2362	5.1128	1701.7	2378.9
19000.	361.43	0.0019260	0.004751	0.006678	1778.7	692.0	2470.6	3.9429	1.0903	5.0332	1742.1	2343.8
20000.	365.70	0.0020370	0.003840	0.005877	1826.5	591.9	2418.4	4.0149	0.9263	4.9412	1789.7	2300.8
21000.	369.78	0.0022015	0.002822	0.005023	1886.3	461.3	2347.6	4.1048	0.7175	4.8223	1840.0	2242.1
22000.	373.69	0.0026714	0.001056	0.003728	2011.1	184.5	2195.6	4.2947	0.2852	4.5799	1952.4	2113.8
22120.	374.15	0.00317	0.0	0.00317	2107.4	0.0	2107.4	4.4429	0.0	4.4429	2037.3	2037.3

TABLE 2

TYPICAL SPECIFIC HEAT VALUES
(at 20°C)

Material	Specific Heat kJ/(kg·°C)
Iron and Low Carbon Steel	0.5
Aluminum	0.92
Copper	0.40
Glass	0.84
Zinc	0.39
Lead	0.13
Tin	0.23
Brass	0.39
Water	4.18
Oil (unused engine oil)	1.88
Acetic Acid	2.03
Acetone	2.16
Aniline	2.06
Benzene	1.74
n-Butyl Alcohol	2.37
Chloroform	.967
Ethyl Acetate	2.01
Ethyl Alcohol	2.47
Ethylene Glycol	2.38
Glycerine	2.43
n-Heptane	1.88
Isobutyl Alcohol	2.30
Methyl Alcohol	2.47
n-Octane	2.18
n-Pentane	2.18
Toluene	1.68
Turpentine	1.80
Air	1.01

TABLE 3

TYPICAL HEAT OF VAPORIZATION VALUES

Material	**Heat of Vaporization kJ/kg**
Water at 20°C	2450
Tri-Chlor Ethylene	230
Acetone	510
Ethyl Alcohol	860
Iso-Propyl Alcohol	675
Benzene	400
Toluene	350
Turpentine	290
Naphtha	240
Kerosene	200
Carbon Tetrachloride	195

TABLE 4

AVERAGE OVERALL HEAT TRANSFER COEFFICIENTS U*

HEATING APPLICATIONS		CLEAN SURFACE COEFFICIENTS		DESIGN COEFFICIENTS Considering Usual Fouling in this Service	
HOT SIDE	COLD SIDE	Nat. Convect	Forc. Convec.	Nat. Convect.	Forc. Convect.
1 Steam	Watery solution	250-500	300-550	100-200	150-275
2 Steam	Light oils	50 - 70	110-140	40 - 45	60-110
3 Steam	Medium lube oil	40 - 60	100-130	25 - 40	50-100
4 Steam	Bunker C or #6 fuel oil	20 - 40	70 - 90	10 - 30	60 - 80
5 Steam	Tar or asphalt	15 - 35	50 - 70	15 - 25	40 - 60
6 Steam	Molten sulphur	35 - 45	60 - 80	4 - 15	50 - 70
7 Steam	Molten paraffin	35 - 45	45 - 55	25 - 35	40 - 50
8 Steam	Air or gases	2 - 4	5 - 10	1 - 3	4 - 8
9 Steam	Molasses or corn syrup	20 - 40	70 - 90	15 - 30	60 - 80
10. High temp. hot water	Watery solutions	80-100	100-225	70-100	110-160
11 High temp. ht. transfer oil	Tar or asphalt	12 - 30	45 - 65	10 - 20	30 - 50
12. Therminol	Tar or asphalt	15 - 30	50 - 60	12 - 20	30 - 50
COOLING APPLICATIONS					
COLD SIDE	HOT SIDE				
13. Water	Watery solution	80-100	150-200	65-125	105-200
14. Water	Quench oil	10 - 15	25 - 45	7 - 10	15 - 25
15. Water	Medium lube oil	8 - 12	20 - 30	5 - 8	10 - 20
16. Water	Molasses or corn syrup	7 - 10	18 - 26	4 - 7	8 - 15
17 Water	Air or gases	2 - 4	5 - 10	1 - 3	4 - 8
18 Freon or ammonia (dir. expan.)	Water solution	35 - 45	60 - 90	20 - 35	40 - 60
19. Calcium or sodium brine	Watery solution	100-120	175-200	50 - 75	80-125

*U = Btu/(h·ft^2·°F)

Note: 1 Btu/(h · ft^2·°F) = 5.68 W/(m^2·°C)

COMMON CONVERSIONS

1 barrel (35 Imp gal) (42 US gal) = 159.1 litres

1 gallon (Imp) = 1.20094 gallon (US)

1 horsepower (boiler) = 9809.6 watts

1 horsepower = 2545 Btu/hour

1 horsepower = 0.746 kilowatts

1 joule = 1 N-m

Kelvin = (°C + 273.15)

1 kilowatt-hour = 3600 kilojoules

1 Newton = 1 kg-m/s^2

1 therm = 10^5 Btu

1 ton (refrigerant) = 12002.84 Btu/hour

1 ton (refrigerant) = 3516.8 watts

1 watt = 1 joule/second

Rankine = (°F + 459.67)

Cubes

1 yd^3 = 27 ft^3

1 ft^3 = 1728 in^3

1 cm^3 = 1000 mm^3

1 m^3 = 10^6 cm^3

1 m^3 = 1000 L

Squares

1 yd^2 = 9 ft^2

1 ft^2 = 144 in^2

1 cm^2 = 100 mm^2

1 m^2 = 10000 cm^2

SI PREFIXES

Prefix	Symbol	Magnitude	Factor
tera	T	1 000 000 000 000	10^{12}
giga	G	1 000 000 000	10^9
mega	M	1 000 000	10^6
kilo	k	1 000	10^3
hecto	h	100	10^2
deca	da	10	10^1
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0.001	10^{-3}
micro	u	0.000 001	10^{-6}
nano	n	0.000 000 001	10^{-9}
pica	p	0.000 000 000 001	10^{-12}

UNIT CONVERSION TABLES
METRIC TO IMPERIAL

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
amperes/square centimetre	A/cm^2	amperes/square inch	A/in^2	6.452
Celsius	°C	Fahrenheit	°F	(°C × 9/5) + 32
centimetres	cm	inches	in	0.3937
cubic centimetres	cm^3	cubic inches	in^3	0.06102
cubic metres	m^3	cubic foot	ft^3	35.314
grams	g	ounces	oz	0.03527
grams	g	pounds	lb	0.0022
grams/litre	g/L	pounds/cubic foot	lb/ft^3	0.06243
joules	J	Btu	Btu	9.480×10^{-4}
joules	J	foot-pounds	ft-lb	0.7376
joules	J	horsepower-hours	hp-h	3.73×10^{-7}
joules/metre, (Newtons)	J/m, N	pounds	lb	0.2248
kilograms	kg	pounds	lb	2.205
kilograms	kg	tons (long)	ton	9.842×10^{-4}
kilograms	kg	tons (short)	tn	1.102×10^{-3}
kilometres	km	miles (statute)	mi	0.6214
kilopascals	kPa	atmospheres	atm	9.87×10^{-3}
kilopascals	kPa	inches of mercury (@ 32°F)	in Hg	0.2953
kilopascals	kPa	inches of water (@ 4°C)	in H_2O	4.0147
kilopascals	kPa	pounds/square inch	psi	0.1450
kilowatts	kW	foot-pounds/second	ft-lb/s	737.6
kilowatts	kW	horsepower	hp	1.341
kilowatt-hours	kWh	Btu	Btu	3413
litres	L	cubic foot	ft^3	0.03531
litres	L	gallons (Imp)	gal (Imp)	0.21998
litres	L	gallons (US)	gal (US)	0.2642
litres/second	L/s	cubic foot/minute	cfm	2.1186
lumen/square metre	lm/m^2	lumen/square foot	lm/ft^2	0.09290
lux, lumen/square metre	lx, lm/m^2	footcandles	fc	0.09290
metres	m	foot	ft	3.281
metres	m	yard	yd	1.09361
parts per million	ppm	grains/gallon (Imp)	gr/gal (Imp)	0.07
parts per million	ppm	grains/gallon (US)	gr/gal (US)	0.05842
permeance (metric)	PERM	permeance (Imp)	perm	0.01748
square centimetres	cm^2	square inches	in^2	0.1550
square metres	m^2	square foot	ft^2	10.764
square metres	m^2	square yards	yd^2	1.196
tonne (metric)	t	pounds	lb	2204.6
watt	W	Btu/hour	Btu/h	3.413
watt	W	lumen	lm	668.45

UNIT CONVERSION TABLES
IMPERIAL TO METRIC

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
ampere/in^2	A/in^2	ampere/cm^2	A/cm^2	0.1550
atmospheres	atm	kilopascals	kPa	101.325
British Thermal Unit	Btu	joules	J	1054.8
Btu	Btu	kilogram-metre	kg-m	107.56
Btu	Btu	kilowatt-hour	kWh	2.928×10^{-4}
Btu/hour	Btu/h	watt	W	0.2931
calorie, gram	cal or g-cal	joules	J	4.186
chain	chain	metre	m	20.11684
cubic foot	ft^3	cubic metre	m^3	0.02832
cubic foot	ft^3	litre	L	28.32
cubic foot/minute	cfm	litre/second	L/s	0.47195
cycle/second	c/s	Hertz	Hz	1.00
Fahrenheit	°F	Celsius	°C	(°F-32)/1.8
foot	ft	metre	m	0.3048
footcandle	fc	lux, lumen/ square metre	lx, lm/m^2	10.764
footlambert	fL	candela/square metre	cd/m^2	3.42626
foot-pounds	ft-lb	joule	J	1.356
foot-pounds	ft-lb	kilogram-metres	kg-m	0.1383
foot-pounds/second	ft-lb/s	kilowatt	kW	1.356×10^{-3}
gallons (Imp)	gal (Imp)	litres	L	4.546
gallons (US)	gal (US)	litres	L	3.785
grains/gallon (Imp)	gr/gal (Imp)	parts per million	ppm	14.286
grains/gallon (US)	gr/gal (US)	parts per million	ppm	17.118
horsepower	hp	watts	W	745.7
horsepower-hours	hp-h	joules	J	2.684×10^6
inches	in	centimetres	cm	2.540
inches of Mercury (@ 32°F)	in Hg	kilopascals	kPa	3.386
inches of water (@ 4°C)	in H_2O	kilopascals	kPa	0.2491

UNIT CONVERSION TABLES
IMPERIAL TO METRIC (cont'd)

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
lamberts	*L	candela/square metre	cd/m^2	3.183
lumen/square foot	lm/ft^2	lumen/square metre	lm/m^2	10.76
lumen	lm	watt	W	0.001496
miles (statute)	mi	kilometres	km	1.6093
ounces	oz	grams	g	28.35
perm (at 0°C)	perm	kilogram per pascal-second-square metre	kg/Pa-s-m^2 (PERM)	5.721×10^{-11}
perm (at 23°C)	perm	kilogram per pascal-second-square metre	kg/Pa-s-m^2 (PERM)	5.745×10^{-11}
perm-inch (at 0°C)	perm. in.	kilogram per pascal-second-metre	kg/Pa-s-m	1.4532×10^{-12}
perm-inch (at 23°C)	perm. in.	kilogram per pascal-second-metre	kg/Pa-s-m	1.4593×10^{-12}
pint (Imp)	pt	litre	L	0.56826
pounds	lb	grams	g	453.5924
pounds	lb	joules/metre, (Newtons)	J/m, N	4.448
pounds	lb	kilograms	kg	0.4536
pounds	lb	tonne (metric)	t	4.536×10^{-4}
pounds/cubic foot	lb/ft^3	grams/litre	g/L	16.02
pounds/square inch	psi	kilopascals	kPa	6.89476
quarts	qt	litres	L	1.1365
slug	slug	kilograms	kg	14.5939
square foot	ft^2	square metre	m^2	0.09290
square inches	in^2	square centimetres	cm^2	6.452
square yards	yd^2	square metres	m^2	0.83613
tons (long)	ton	kilograms	kg	1016
tons (short)	tn	kilograms	kg	907.185
yards	yd	metres	m	0.9144

* "L" as used in Lighting

4138T/T33(-2)

The following typical values for conversion factors may be used when actual data are unavailable. The MJ and Btu equivalencies are heats of combustion. Hydrocarbons are shown at the higher heating value, wet basis. Some items listed are typically feedstocks, but are included for completeness and as a reference source. The conversion factors for coal are approximate since the heating value of a specific coal is dependent on the particular mine from which it is obtained.

ENERGY TYPE	METRIC	IMPERIAL
COAL		
— metallurgical	29 000 megajoules/tonne	25.0×10^6 Btu/ton
— anthracite	30 000 megajoules/tonne	25.8×10^6 Btu/ton
— bituminous	32 100 megajoules/tonne	27.6×10^6 Btu/ton
— sub-bituminous	22 100 magajoules/tonne	19.0×10^6 Btu/ton
— lignite	16 700 megajoules/tonne	14.4×10^6 Btu/ton
COKE		
— metallurgical	30 200 megajoules/tonne	26.0×10^6 Btu/ton
— petroleum		
— raw	23 300 megajoules/tonne	20.0×10^6 Btu/ton
— calcined	32 600 megajoules/tonne	28.0×10^6 Btu/ton
PITCH	37 200 megajoules/tonne	32.0×10^6 Btu/ton
CRUDE OIL	38.5 megajoules/litre	5.8×10^6 Btu/bbl
No. 2 OIL	38.68 megajoules/litre	5.88×10^6 Btu/bbl $.168 \times 10^6$ Btu/IG
No. 4 OIL	40.1 megajoules/litre	6.04×10^6 Btu/bbl $.173 \times 10^6$ Btu/IG
No. 6 OIL (RESID. BUNKER C)		
@ 2.5% sulphur	42.3 megajoules/litre	6.38×10^6 Btu/bbl $.182 \times 10^6$ Btu/IG
@ 1.0% sulphur	40.5 megajoules/litre	6.11×10^6 Btu/bbl $.174 \times 10^6$ Btu/IG
@ .5% sulphur	40.2 megajoules/litre	6.05×10^6 Btu/bbl $.173 \times 10^6$ Btu/IG
KEROSENE	37.68 megajoules/litre	$.167 \times 10^6$ Btu/IG
DIESEL FUEL	38.68 megajoules/litre	$.172 \times 10^6$ Btu/IG
GASOLINE	36.2 megajoules/litre	$.156 \times 10^6$ Btu/IG
NATURAL GAS	37.2 megajoules/m^3	1.00×10^6 Btu/MCF
PROPANE	50.3 megajoules/kg 26.6 megajoules/litre	$.02165 \times 10^6$ Btu/lb $.1145 \times 10^6$ Btu/IG
ELECTRICITY	3.6 megajoules/kWh	$.003413 \times 10^6$ Btu/kWh