



Practical guide to the selection of condensers

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PRACTICAL GUIDE TO THE SELECTION OF CONDENSERS

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. PURPOSE AND SCOPE OF THIS DATA ITEM	2
3. PROCESS OF CONDENSATION	3
3.1 Cooling curve	3
3.2 Subcooling of Condensate	3
3.3 Heat Transfer in Condensation	3
3.4 Flow Through Condensers	4
3.5 Part-Load Operation	4
4. COOLANT	5
4.1 Choice Between Air and Water as Coolant	5
5. DATA REQUIRED	7
6. TYPES OF CONDENSER TO BE CONSIDERED	8
6.1 Direct-contact Condensers	8
6.1.1 Sparge pipes	8
6.1.2 Spray condensers	8
6.1.3 Tray-types	10
6.1.4 Packed columns	11
6.2 Tube-side Condensers	11
6.2.1 Vertical tubes	12
6.2.2 Horizontal tubes	12
6.2.3 Inclined Tubes	13
6.2.4 Note on subcooling of condensate	13
6.2.5 Counter-current flow of vapour and condensate	14
6.3 Shell-side Condensers – Horizontal	14
6.3.1 Shell-side downflow (TEMA shell type X)	15
6.3.2 Shell-side crossflow (TEMA shell-type E, F, G, H or J, with baffles)	16
6.3.3 Note on the use of finned tubes	17
6.4 Shell-side Condensers – Vertical	17
6.4.1 Note on de-superheating	18
6.4.2 Note on enhanced heat transfer on vertical tubes	18
6.5 Graphite Heat Exchangers as Condensers	18
6.6 Coiled-tube Condensers	19
6.7 Plate Heat Exchangers as Condensers	20

6.7.1	Spiral plate condensers	20
6.7.2	Plate-fin condensers	21
7.	FAILURES IN OPERATION	22
7.1	Fouling by the Coolant	22
7.2	Fouling by Condensate or Vapour	22
7.3	Corrosion by the Coolant	22
7.4	Corrosion by Condensate or Vapour	23
7.5	Temperature Pinch	23
7.6	Avoidance of Stagnant Zones	24
7.7	Parallel Path Instability	24
7.8	Draining	24
7.9	Frozen Condensate	24
7.10	Fogging	25
7.11	Frost on Fins	25
7.12	Contamination	26
7.13	Erosion	26
8.	GUIDE FOR SELECTION OF CONDENSER TYPES	27
9.	GLOSSARY	32
10.	REFERENCES	34

PRACTICAL GUIDE TO THE SELECTION OF CONDENSERS

1. NOTATION AND UNITS

Two sets of self-consistent units are given; the SI and the British

		<i>Units</i>	
		<i>SI</i>	<i>British</i>
A	total surface area for heat transfer	m^2	ft^2
$\dot{M}$	mass flow rate	kg/s	lb/h
$\dot{m}$	mass flux ($= \dot{M}/S$)	kg/s m^2	lb/h ft^2
p	static pressure	N/m^2 (Pa)	lbf/ft^2
$\dot{q}$	heat flux ($= \dot{Q}/A$)	W/m^2	Btu/h ft^2
$\dot{Q}$	rate of heat transfer	W	Btu/h
S	cross-sectional area for flow	m^2	ft^2
T	temperature	K	$^{\circ}\text{F}$
U	overall heat transfer coefficient	$\text{W/m}^2 \text{ K}$	$\text{Btu/h ft}^2 ^{\circ}\text{F}$
x_g	quality		
α	heat transfer coefficient of condensate	$\text{W/m}^2 \text{ K}$	$\text{Btu/h ft}^2 ^{\circ}\text{F}$
Δp	pressure drop	N/m^2	lbf/ft^2
ρ	density of fluid	kg/m^3	lb/ft^3

Subscripts

c	coolant
i	incondensables
in	at inlet
out	at outlet
s	under conditions of saturation
v	vapour to be condensed
x	a location within condenser where conditions are known, for calculation of pressure gradient and heat flux

Throughout the text pressures are given in bar: one bar is equal to 10^5 Pa or 14.5 lbf/in^2 .

2. PURPOSE AND SCOPE OF THIS DATA ITEM

Condensers are widely used in the process industries, operating at rates of heat transfer up to 40 MW and pressures from deep vacuum to 200 bar. The vapour may be pure or multi-component and contain gas which will not condense (known as ‘incondensables’ or ‘inerts’). Coolers, where the fluid to be cooled is a gas containing some vapour that is partially condensed, are also discussed.

The purpose of this Data Item is to assist the engineer in the process industries under changed process conditions, to choose the most suitable type of condenser for a specified duty, predict performance or investigate why a condenser is not operating satisfactorily.

In addition the Item serves as an introduction to other Data Items dealing with the thermal and hydraulic design of various types of condenser (Reference 15).

The duties for which a condenser may be required in the process industries are many; this Data Item discusses those required for:—

- (1) condensing steam exhausted under vacuum from a turbine;
- (2) condensing vapour from an evaporator;
- (3) condensing single and mixed process vapours;
- (4) cooling a process gas which contains a vapour that condenses as it is cooled;
- (5) condensing a vapour from a distillation column or reaction vessel (a “reflux condenser”) returning the condensate;
- (6) condensing a heat transfer fluid, *e.g.* in a refrigeration plant, a heat pump, or an air-conditioning plant.

Duties are not included here are heaters where the source of heat is condensing steam, *e.g.* a reboiler, and thermosyphon heat pipes, described in Reference 10.

Section 3 contains an introduction to the process of condensing in a heat exchanger.

The coolant may be specified, or the designer may have an option between several systems. The range of coolants considered is listed in Section 4, which discusses their relative merits. Section 5 gives the process data that the designer of the condenser must obtain from the process designer.

Section 6 describes the many types of condenser that are available for the duties listed above. There are many potential difficulties in the operation of a condenser, any one of which may influence the choice of condenser type. They are discussed in Section 7.

Section 8 contains flow charts which give advice on the choice of the most suitable condenser for each of the six duties considered in this Data Item.

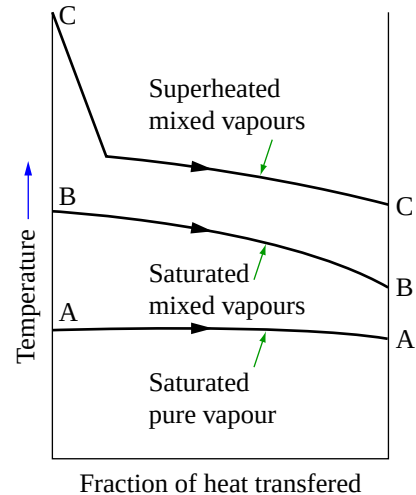
A glossary of the specialised terms used in this Data Item is given in Section 9.

3. PROCESS OF CONDENSATION

This Section describes the heat transfer and fluid flow involved in condensing a vapour in a heat exchanger.

3.1 Cooling curve

This gives the relationship between the amount of heat removed from the vapour and the temperature of the vapour, assuming that the vapour and condensate are intimately mixed. Sketch 3.1 shows some typical cooling curves. The vapour may be wet initially; if it is a single-component (pure) vapour, the cooling curve will approximate to a horizontal straight line, as shown by the line AA. The slight fall in temperature is due to the pressure drop in the condenser. With a multi-component vapour, or if incondensables are present, there is a considerable drop in temperature along the condenser as the less volatile components condense, as shown by the line BB.



Sketch 3.1 Some typical cooling curves

The incoming vapour may be superheated, in which case the cooling curve takes the form shown by the line CC. If the incoming vapour is highly superheated, the temperature of the cooled surface where the vapour enters may be above the saturation temperature, so no condensation will occur; this is called the 'dry desuperheating zone'. As the vapour is cooled, the temperature of the surface falls. When this reaches the saturation temperature, condensation on the cooled surface begins. The region from here to the place where the bulk of the vapour is cooled to the saturation temperature is called the 'wet desuperheating zone'.

3.2 Subcooling of Condensate

The process designer may specify some subcooling of the condensate. A few degrees of subcooling will always occur, but the exact amount is difficult to predict. If a considerable amount is required, it is best to use a separate drain-cooler. Some types of condenser give more subcooling than others, as discussed in the appropriate sub-sections of Section 6.

3.3 Heat Transfer in Condensation

In normal industrial condensers, the condensate that forms on the cooled surface completely wets the surface and drains off it as a film. At low rates of flow of vapour and of condensate, this film is laminar and the surface smooth. Consequently the heat transfer coefficient for condensate equals the thermal conductivity of the liquid divided by the thickness of the film. At higher liquid flow rates there is some enhancement in heat transfer coefficient because of increased surface area due to the formation of waves on the surface. At even higher rates, the flow of the liquid becomes turbulent and there is a considerable increase in the heat transfer coefficient. Downward flow of vapour enhances heat transfer by reducing the thickness of the film.

With mixed vapours and in the presence of incondensables there is a further resistance to heat transfer in the gas phase.

The estimation of the heat transfer coefficient in condensation is described in many books on heat transfer, e.g. References 1 and 11.

3.4 Flow Through Condensers

The first problem is to design an inlet system that will distribute the incoming vapour evenly to the cooled regions. Maldistribution of vapour affects the thermal performance, especially if a high thermal effectiveness is required, and with mixed vapour or incondensables. However it is important to avoid excessive pressure drop in the inlet system, as this reduces the saturation temperature and so reduces the thermal performance. The estimation of the pressure drop at the inlet to the shell of a shellside condenser is described in Section 4.4 of ESDU¹⁵.

A serious problem in the design of a baffled shellside condenser arises from the fact that the fluid does not all flow across the bundle of tubes in the direction prescribed by the baffles; some flows around the bundle through the space between the bundle and the shell, and some leaks between the baffle and the tubes and between the baffle and the shell. A method of estimating the fractions flowing through these parallel paths is given in ESDU¹² for single-phase flow. It is not yet known how to extend these methods to condensation.

In baffled shell-and-tube heat exchangers the segmental baffles are normally arranged so that the straight cut is horizontal, as shown in Figure N-2 of the Standards of the Tubular Exchangers Manufacturers' Association (TEMA)⁸. In condensers the cut is more often vertical, to reduce pressure drop and avoid unsteady flow. Consequently there is some separation of the phases, the condensate gravitating to the bottom of the shell. In completely separated flow, the level of condensate adjusts itself so that the pressure drop per baffle space of the liquid equals that of the vapour. Thus there is little or no liquid on the bottom of the shell near to the inlet, but the level increases towards the outlet.

It is important to have an adequate drain at the condenser outlet to remove the condensate (see Section 7.8) and an adequate, correctly located vent, or vents to remove incondensables. During start-up and throughout operation the air or inert gas in the condenser must be removed. Even a nominally pure vapour may contain traces of incondensables, which would collect in regions of low velocity, blanketing the condenser surface and reducing heat transfer.

When a condenser is operating under vacuum, the vent must be capable of removing not only the incondensables in the incoming vapour but also the air that leaks into the system. In this case an ejector or gas vacuum pump is required. The steam leaving a turbine under vacuum contains air that has leaked through the gland at the outlet of the turbine. The large steam condensers on Power Plants have vacuum pumps to extract the air and associated vapour. On the smaller condensers used for condensing exhaust from turbines in chemical plant, it is more usual to use a steam-driven ejector. Normally it is necessary to use two or three such ejectors arranged in series, with inter-stage surface condensers. The driving fluid for these ejectors is steam at a pressure of 10 to 20 bar. The driving and entrained steam mix in a converging pipe and each ejector is capable of giving a pressure ratio of 3 to 4. They are normally designed by proprietary manufacturers of equipment for steam plants.

With air-cooled condensers an additional problem arises from the need to have a uniform distribution of air entering across the bundles of tubes.

3.5 Part-Load Operation

Heat exchangers are usually designed for operation under flow-sheet conditions. This seldom happens in reality. The flow rates may be anything from say 50% to 120% of that specified. Temperatures and compositions may differ. The amount of fouling (see Sections 7.1 and 7.2) will be less than that assumed in design when the exchanger is clean, but it will increase over several months of operation until it reaches an equilibrium value, which may exceed that assumed in design. These changes in conditions may seriously affect the behaviour of a condenser and of the plant of which it is part. It is therefore desirable to carry out

rating calculations to determine the performance of the condensers under various abnormal conditions, if it is suspected that plant operation may be upset.

4. COOLANT

The following coolants are considered:

- (1) a process fluid requiring to be heated;
- (2) ambient air;
- (3) water taken from a lake, river or sea (surface water);
- (4) water circulated through a water cooling tower;
- (5) a boiling liquid, *e.g.* a refrigerant;
- (6) condensate from a direct contact condenser circulated through a separate cooler.

Normally the inlet and outlet composition, flow rate and temperatures of the coolant will be specified. With coolants (2), (3) and (4), the inlet temperature will be specified, but the designer will have some freedom in the choice of flow rate and consequently of the outlet temperature of the coolant.

4.1 Choice Between Air and Water as Coolant

If waste heat cannot be reclaimed, coolant (3) is the first choice for heat rejection, provided that there is sufficient surface water available at an adequately low temperature, and the extra heat load will not significantly increase the temperature of the surface water. Otherwise the process designer must choose between a dry heat rejection system (2), in which heat is transferred directly to atmosphere, and a wet system (4), in which heat is transferred to cooling water which is then circulated through a cooling tower where it rejects the heat to atmosphere, mainly by evaporative cooling.

For a given rate of heat transfer, a water-cooled shell-and-tube heat exchanger is less expensive than an air-cooled exchanger, because water has a greater cooling capacity than air. However with a wet system there is the extra expense of the water cooling tower. The wet system is cheaper when a close approach to the ambient temperature is required, because the cost of the heat exchanger then exceeds the cost of the cooling tower. Conversely the dry system is cheaper when a low thermal effectiveness is required. As a guide for preliminary considerations, water cooling is cheaper than air cooling where the difference between the temperature of the vapour and the coolant is less than 20°C.

On plants where there are many coolers, air cooling may be used for the duties at higher temperatures and water cooling for the duties at lower temperatures. If a large process stream must be cooled over a wide range of temperature, it may be cheapest to use air cooling for the initial cooling, followed by water cooling for the final stages of cooling (in what is called 'a trim cooler').

Other factors that influence the choice between air and water are summarised below.

Space. Air-cooled heat exchangers occupy considerably more space, although the space underneath them may be used for equipment or storage. They must be far enough from trees and buildings to avoid recirculation of air.

Summer heat. Air cooler performance deteriorates much more rapidly in hot weather than do exchangers and condensers using cooling water (Section 4.1).

Rain and hail. A sudden shower leads to a marked increase in the cooling provided by an air-cooled condenser, and this might upset the control of the plant. Hail damages the fins on the tubes in the top row of an air-cooled condenser.

Environmental factors. An air-cooled heat exchanger requires much more air and hence its fans produce more noise than a water cooling tower at the same heat load. Except when the relative humidity is very low, water cooling towers produce a visible plume of moist air, which may considerably impair nearby visibility or corrode local steelwork, especially if the plant is in a valley. Hybrid systems are available in which wet cooling and dry cooling are employed in one tower in such a way that the combined streams of effluent air can never be saturated.

Pressure of process fluid. If the process fluid is at high pressure, the problems in mechanical design are eased with air-cooled condensers.

Power failure. Water-cooled plants are shut down immediately, whereas air-cooled condensers provide some cooling by natural draught.

Manifolds. If the process fluid is under deep vacuum, larger manifolds are needed for air-cooled than for water-cooled condensers; they are expensive.

Cleaning. The outside of the tubes of air-cooled condensers can be easily cleaned, without a plant shutdown, by washing or other means.

Make-up water and purge. Water-cooling towers need make-up water to replace the water lost by evaporation and purged to control the amount of dissolved solids in circulation, hence they cannot be used in arid places. The disposal of the purge is made difficult by the need to use toxic materials for water treatment.

Ice. May form at the air entry to a water cooling tower when the ambient temperature is below 0°C.

5. DATA REQUIRED

The following quantities are required for the calculations in thermal rating and design.

$\dot{M}_c$	mass flow rate of coolant
$\dot{M}_i$	mass flow rate of incondensables
$\dot{M}_{v\ in}$	mass flow rate of vapour at inlet
$\dot{M}_{v\ out}$	mass flow rate of vapour at outlet
$\dot{Q}$	rate of heat transfer (heat load)
p	operating pressures of vapour and coolant if greater than 20 bar
Δp	permitted pressure drop of vapour and coolant
$T_{v\ in}$	inlet temperature of vapour
$T_{v\ out}$	outlet temperature of vapour, condensate and incondensables
T_s	saturation temperature at pressure p
$T_{c\ in}$	inlet temperature of coolant
$T_{c\ out}$	outlet temperature of coolant (calculated from heat balance)

In addition to the above, it is necessary to know the thermal resistances due to fouling and the thermodynamic and transfer properties of the fluids. With mixed vapours it is also important to know the composition at inlet.

6. TYPES OF CONDENSER TO BE CONSIDERED

Direct contact condensers, described in Section 6.1, are the cheapest. They differ from the surface condenser described in Sections 6.2 to 6.7 in that the vapour to be condensed is intimately mixed with the cooling liquid inside a vessel, so that heat is transferred directly from the hot stream to the cold stream (usually of the same composition as the condensate). Otherwise the two streams are separated by a surface, which takes the form of tubes or plates, through which the heat is transferred by conduction. Tubular condensers are described in Sections 6.2 to 6.6. The plate-type condensers described in Section 6.7 are likely to be less expensive than tubular condensers, but they are not suitable if the volumetric rate of flow of vapour considerably exceeds that of the coolant. The restrictions on the maximum temperature and pressure are more stringent with plate-type than with tubular condensers.

6.1 Direct-contact Condensers

These may be used only if the coolant is water or a process liquid, and if the vapour and the coolant are at the same pressure. They may not be used if the condensate must be kept separate from the coolant. Direct-contact condensers are less prone than surface condensers to troubles resulting from the use of dirty or corrosive fluids or from superheat in the vapour. Heat transfer rates per unit volume are high in direct-contact condensers provided that an intimate mixing of the two streams can be achieved. The mixture of condensate and coolant must either be put to drain or be cooled in a separate tubular or plate heat exchanger where the heat is rejected to a sink, such as the ambient air or surface water. In some applications, contamination of the outgoing vapours and gases by the coolant may cause trouble. Direct-contact condensers are used mainly in applications operating under vacuum or at a low pressure above atmospheric.

Four types of direct-contact condenser are described in the next paragraphs. These have been designed to produce efficient mixing of vapour and cooling liquid. Information on the design of direct-contact steam condensers is given in Reference 4 and on process condensers in Reference 5.

6.1.1 Sparge pipes

The simplest direct-contact condenser is the sparge pipe, consisting of one or several horizontal perforated pipes submerged in the coolant contained in a vessel. The cross-sectional area of each pipe should be at least twice the total cross-sectional area of the holes in it, to achieve good distribution along the length of the pipe. The depth of liquid above the pipes must be sufficient for the bubbles to condense before reaching the surface; this is to some extent dependent on the diameter of the holes and the required approach of the coolant to the saturation temperature of the vapour. The pressure in the pipe must considerably exceed the static head of liquid to prevent coolant entering the pipe and generating shock waves ("water hammer") which creates noise and may cause mechanical damage. Consequently, it is not possible to reduce the flowrate of the process stream greatly by throttling the flow of the incoming vapour. For a wide range in throughput, several pipes must be used, each with its own valve for control or isolation. Sparge pipes are not suitable if a temperature approach closer than 10°C is required.

More intimate mixing of vapour and coolant can be achieved using an injector submerged in the coolant. The vapour is introduced through the nozzle of the injector, entraining the coolant and returning the coolant to the vessel at the same pressure.

6.1.2 Spray condensers

The most commonly used form of direct-contact condenser is the spray condenser. Two are described by the Heat Exchange Institute⁴ and illustrated in Sketches 6.1 and 6.2. The spray nozzle must be designed to produce small drops and must be positioned so that the drops are well distributed within the vessel. Performance is impaired if the drops impinge too readily on the wall of the vessel. Too fine a spray results