Direct heat exchangers in the food industry

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7.1 Introduction

Heat refers to a type of energy as the molecules of a substance move in lockstep. The absolute temperature is proportional to the substance's mean kinetic energy per molecule. Because of the temperature difference among different materials, thermal energy starts to move and transfer from one to another. The spontaneous, irreversible flow of heat from hotter (higher temperature) substances to the colder (lower temperature) substances is known as heat transfer. This field of study focuses on the analysis and quantification of heat transfer. The science of heat flow and its relationship to mechanical work is known as thermodynamics. The principle of energy conservation is well known as the first law of thermodynamics. Except in subatomic processes, energy cannot be created or destroyed and it can only be transformed from one form to another. The terms "work" and "heat" are interchangeable. Unless there is an energy storage component, the energy output must match the energy input. Moreover, the second law of thermodynamics is that heat transmission may only occur in one direction, which is from a hotter substance to a colder one or from a higher to a lower energy state, just like water flow which takes place only downhill. Heat does not flow from a low-temperature substance to a high-temperature one spontaneously. A device can only provide heat in the reverse direction if it receives external energy. Any device or equipment that performs work must have an energy source and operation units, which means that energy must flow through the machine. However, only a portion of this flow may be converted into work (Savulescu, Sorin, & Smith, 2002).

7.2 Direct heat-transfer mechanism

Heat can be transferred from one system to another resulting in a temperature change. Thermodynamic research examines the amount of heat transfer that occurs as a system moves from one equilibrium state to another. The study of heat transfer focuses on understanding the mechanism of this energy exchange. Heat flows from a higher-temperature substance into a lower-temperature substance. When both substances reach the same temperature, heat transfer ends. There are three ways of heat transfer;

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they are conduction, convection, and radiation. All forms of heat transmission need a temperature difference. Conduction, convection, and radiation use indirect heat transfer to cause temperature change, whereas conduction and convection are usually direct heat-transfer mechanisms (Cengel & Ghajar, 2020; Welty, Rorrer, & Foster, 2020). Conduction heat transfer is a status of molecular-level kinetic energy transfers between solids, liquids, and gases. In solids, heat conduction and electrical conduction have a tight relationship. Conduction heat moves in the direction of low temperature. Convection heat transfer is a result of larger-scale motions of a fluid, either liquid or gas. The rate of convection heat transfer increases as the fluid flow velocity increases. Radiation heat transfer is the energy transition with electromagnetic waves. Radiation can occur without any substance present other than the surface exchanging energy. The presence of two surfaces with different temperatures is the only requirement for the occurrence of radiation heat transfer. To generate internal energy, radiation must be absorbed by matter. For example, solar energy is transmitted from the sun to earth by means of radiation (Baehr & Stephan, 2008; Bergman, Incropera, DeWitt, & Lavine, 2011).

Conduction is a direct heat-transfer mechanism in which the energy transfer from a substance occurs from more energetic particles to nearby less energetic particles because of particle interactions. Conduction can occur in solids, liquids, and gases. The geometry, the thickness, the property of a medium, and the temperature difference between the media determine the rate of heat conduction. High molecular energies are usually involved in high temperatures. When nearby molecules collide, energy must be transferred from the more energetic to the less energetic molecules. Energy transfer via conduction must proceed in the direction of a lower temperature in the presence of a temperature gradient. Molecular collisions help with energy transmission, and energy diffusion is a net energy transfer caused by random molecule motion (Holman, 2008; Szokolay, 2012). When two substances with different temperatures come into physical contact, direct contact heat transfer can occur. The implication is that the two substances do not have a barrier between them. Indirect heat transfer occurs when there is a surface wall between the two streams (Kreith & Boehm, 2013; Rajput, 2019).

Applications of direct contact heat exchangers in the food industry have been in different products, such as dairy foods, beverages, oils, and innovative products (Demirci, Lee, Çavuş, & Çağlar, 2020). Direct contact heat transfer can occur at the interface of two continuous streams. For example, a dispersed spray injected into a gaseous or water vapor might contain the condensation of the water vapor with the spray droplets. Besides, a hot gas or fuel might be vaporized and combusted while a gas drifts across a thin liquid sheet. Direct contact heat transfer can occur at the interface of two continuous fluid streams. For example, a hot gas may be vaporized or the fuel can be combusted when the gas flows over a thin liquid film. Furthermore, a dispersed spray injected into a gaseous or vapor stream could cause vapor condensation on droplets inside the spray. Another example is the cooling of small liquid droplets that are solidifying, such as during the production of metal shot or glass beads. Many bioactive compounds are sensitive to many external factors, such as oxygen, light, and heat during the process of heat exchange (Ashaolu et al., 2021; Lee, Tomas, & Jafari, 2020). Chemical interactions between the mass streams can occur in many circumstances of direct-contact heat transfer, and one of the gas streams may be entirely devoured by the other. The sensible heat transfer can occur within two immiscible liquids. When mass fluids contain at least one kind of stream, it can be either laminar flow or turbulent (streamline) flow. Because turbulence might cause difficulties with the mass stream or the dynamic changes in the bulk fluid, turbulence should not allow in many industrial applications (Jacobs, 1995).

Industrial direct heat exchangers have been classified based on the following:

1) Phase characteristics of the contacting fluids
2) The relative flow directions
3) The dynamic forces of the flows
4) Process purposes
5) Heat-transfer surfaces
6) Constructions
7) Phase change mechanisms

These classifications are mentioned in Table 7.1. This chapter will discuss different types of direct heat exchangers for more details according to phase characteristics of the contacting fluids, process purpose, heat-transfer surfaces, and phase change mechanisms (Shah & Sekulic, 2003; Thulukkanam, 2000).

Table 7.1 Classifications of direct heat-transfer processes.

Classified by	Types	Remarks
Phase characteristics of the contacting fluids	Liquid-liquid Solid-gas Gas-liquid *Immiscible fluid* Liquid-vapor	Heat is allowed to transfer in direct contact between any combinations of substance fluids effectively. These phases contain liquids (water), gases (air), vapor, solids, and *immiscible fluids*
The relative flow directions	Parallel flow Counter flow Cross flow	The selection of a specific flow direction is affected by many parameters, including streamflow pathways, device designs, thermal stresses, heat exchanging efficiency, and required temperature
The dynamic forces of the flows	Gravity Pressure Centrifugal forces	Gravity is the most common driving factor for the separation of two immiscible fluids from the other. However, when a force other than gravity is used, pressure or centrifugal forces may be involved in this situation
Process purposes	Steam-driven jet heat exchangers Cooling towers Scrubbers	For different functions and applications in the industry, a variety of heat exchangers are designed and developed. For example, the fluid in the steam-driven jet heat exchanger with a greater pressure at high speed is expelled from the nozzle. The

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Table 7.1 Continued

Classified by	**Types**	**Remarks**
	Hybrid condensers	low-pressure fluid is injected into the mixing chamber, where it comes into direct contact with the jet fluid for heat transfer and then flows into the diffuser together. The output of the diffuser is delivered to the user after it achieves the same pressure and temperature
Heat-transfer surfaces	Drop- or spray-type Jet- or sheet-type Film type Bubble- or pool-type	These types of heat exchangers are classified with the contact surface between two fluids during heat exchange. For example, a film-type heat exchanger allows one kind of fluid to exchange heat with another type of liquid in the form of a liquid film
Constructions	Tubular or shell heat exchangers Plate heat exchangers Extended surface heat exchangers Regenerators	The type of exchanger is designed as a recuperator to allow the heat transfer from the hot stream to the cold stream through a separating wall. The tubular or shell type contains a double pipe and coiled tube. The plate-type contains lamella, panel coils, brazed types, and spiral types. The extended surface type includes tubes and plate fins
Phase change mechanisms	Condenser Evaporator	This mechanism of heat transfer between two fluids usually occurs in two-phase convection. Condensers cool down the gas (air) or liquid (water). Besides, evaporators turn the liquid (water) form into a gas (vapor) form

7.3 Direct heat exchangers classified by process purpose

This section will mention various direct heat exchangers based on their process purposes. Condensers, evaporators, cooling towers, flash evaporators, and scrubbers are the examples.

7.3.1 Condensers

The condenser is a type of heat exchanger and also a component of the refrigeration system. The heat exchanging system is an exothermic process because it can transform a gas or vapor into a liquid and transfer the heat inside the tube to the surrounding air near the tube very efficiently. This is the reason that there is a relatively high temperature in the condenser and its nearby environment. In the refrigeration industry, the refrigerants ammonia and freon are commonly manufactured by condensers. During the distillation process, the function of a condenser is to convert a vapor to a liquid by removing the heat from the gas and steam. Direct-contact condensers have been designed and applied in various industries for more than 100 years. In 1903, Hausbran described the commercial design of barometric condensers theoretically in his book "Evaporating Condensing and Cooling Apparatus" (Hausbrand, 1919). Afterward, the design of direct-contact condensers in 1956 and 1972 appeared and was published (Fair, 1972; How, 1956). Most of the work described is more suitable for cooling gases than steam condensation. In 1977, the report "Direct Contact Condensers-A Literature Survey" was published from the U.S. Department of Energy (Jacobs & Fannar, 1977). Based on the interface formation of steam and the coolant liquid, a direct contact condenser was first introduced into four types: drop- or spray-type, jet- or sheet-type, film type, and bubble- or pool-type. These classifications are still used currently and also in this chapter. The application of the direct contact condenser on deaerators and their potential in geothermal systems was reported (Oliker, 1977; Oliker & Permyakov, 1971). Twenty-one companies in western Europe and the United States produced direct contact equipment, and 13 of them built condensers (Goldstick, 1981). Nowadays, direct contact condensers can be found in a variety of applications, including nuclear reactors; solar energy, geothermal, or space power plants; water desalination; ocean thermal energy conversion systems; and all kinds of chemical or food processing industries (Ashoor, Mansour, Giwa, Dufour, & Hasan, 2016; Bharathan, Parsons, & Althof, 1988; Fisher & Wright, 1984; Najafabadi, 2015). This is because the advantages of the application of direct contact condensers contain simple design and construction, a high efficiency of heat transfer, nonfouling and nonscaling situations, low cost for built-in equipment, and easy maintenance (Hewitt, Shires, & Bott, 1994).

7.3.1.1 Drop- or spray-type condensers

The condensation in drop-type or spray-type condensers occurs when a liquid coolant is injected with spraying or dropping into a steam chamber full of a gas-vapor mixture. The drops can be presumed sphere-shaped, and the transient conduction would direct the heat transfer inside the drops (Kutateladze & Borishanskiĭ, 1966). The spherical surface of drops was rapidly contacted to the hot steam at the saturation temperature. Its instant heat transfer can be exhibited by the experimental equations of transient conduction (Ford & Lekic, 1973). In the drop-type or spray-type condenser, cold water is injected from the upper nozzle, and steam enters the side inlet. After the steam contacts the cold water, it is condensed into water. At the same time, the condensed liquid flows down the pipe, and the noncondensable vapor would also be exhausted. The drop-type or spray-type condenser includes a condensation chamber with a heat exchanger. The bottom of the condensation chamber is provided with a spray water collection tank. A spray pump is installed on the side of the spray water collection tank. The spray pump is connected to a water pipe. The water pipe leads into the condensing chamber. The water pipe is equipped with a spray device on a condensing chamber. The upper end of the heat exchanger is provided with a refrigerant vapor

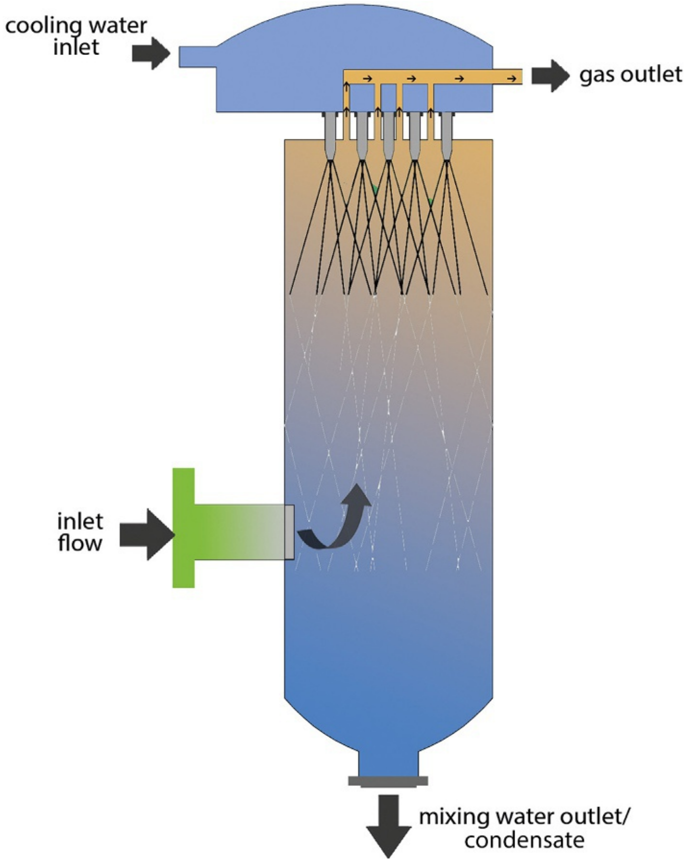

Fig. 7.1 Spray-type condenser.

inlet, and the lower end is provided with a refrigerant vapor outlet. A schematic representation of a spray-type condenser could be seen in Fig. 7.1. In some modern spray-type condensers, a splash-proof water inlet style grille is designed between the heat exchanger and the spray collection tank, and the top of the condensing chamber contains a water collector. Besides, the fluid is driven by the main circulating pump, and the fan is replaced with a spray device. When the circulating cooling water is sprayed, the outside air is pumped in without pressure. The water and air undergo heat exchange during the mixing process (Apriyanti, Adriansyah, Abdurrachim, & Pasek, 2018; Tissot et al., 2014).

7.3.1.2 Jet- or sheet-type condensers

There is direct contact between exhaust vapor and cooling water in jet- and sheet-type condensers used broadly for decades commercially. The cooling water and exhaust vapor are mixed up in a chamber. The temperatures of cooling water and the condensate are the same while being released from the condensers. The condensate would not be recycled and reused to the boilers as feed water. Because the vapor and cooling water are mixed up very well in the chamber of a jet-type condenser, it requires less amount of cooling water for the condensation of the vapor to achieve the high-efficiency process of condensation. Moreover, the advantages of jet-type condensers include simplicity in construction, building space saving, and low cost. The jet condensers are classified into three types:

1) Low-level jet condensers including the parallel flow type and counter flow type.
2) High-level jet condenser or barometric jet condenser.
3) Ejector condenser.

The major components of the jet condenser include nozzles or distributors of the condensing water, a steam inlet, a hot well, and a mixing chamber. If the steam and water flow in the same direction in the mixing chamber before condensation, it is a parallel flow-type jet condenser. However, the steam and water move in the opposite direction in a counter-flow-type chamber. The construction and elements of the sheet-type condenser are very similar to those of the jet-type condenser. The difference is that the coolant liquid flows into the steam chamber as sheet forms instead of a liquid jet. The purpose of both types of condensers is to increase the contact area between cooling water and steam (Bakay & Jaszay, 1978; Kreith & Boehm, 2013). The direct contact jet- and sheet-type condensers are shown schematically in Figs. 7.2 and 7.3 individually.

7.3.1.3 Film-type condensers

The structure of the film-type condenser is more intricate than the two previous types. In the chamber of the film-type condenser, there is a solid surface composed of plats, baffles, or particles. The condensate attaches the surface to form a thin liquid film that slumps down because of the gravity effect. This design offers a huge surface area for heat transfer in the packed bed. In addition, film condensation could lead to low heat-transfer rates because the heat transfer is hindered by the condensate film (Chung, Kim, & Ahmadinejad, 2008). The heat-transfer rate between the steam and surface is decreased by the thermal resistance caused by the film. Many factors can affect the thickness of film formation, such as liquid viscosity, condensation rate, and the orientation of the surface (Camaraza-Medina et al., 2019; Del Col, Parin, Bisetto, Bortolin, & Martucci, 2017).

Film-type condensers are also called packed bed condensers because the coolant flows over a solid substrate to form a thin film. After the steam enters the side pipe, the cooling water is sprayed from the upper side of the contact chamber of the condenser, which is filled with ceramic ring packing. After the packing is wetted by water, the contact area between cold water and steam is increased. The steam is condensed to water and discharged out along the lower pipeline. The noncondensable gas within the upper pipeline is pumped out by the vacuum pump to ensure a certain degree of vacuum in the condenser.

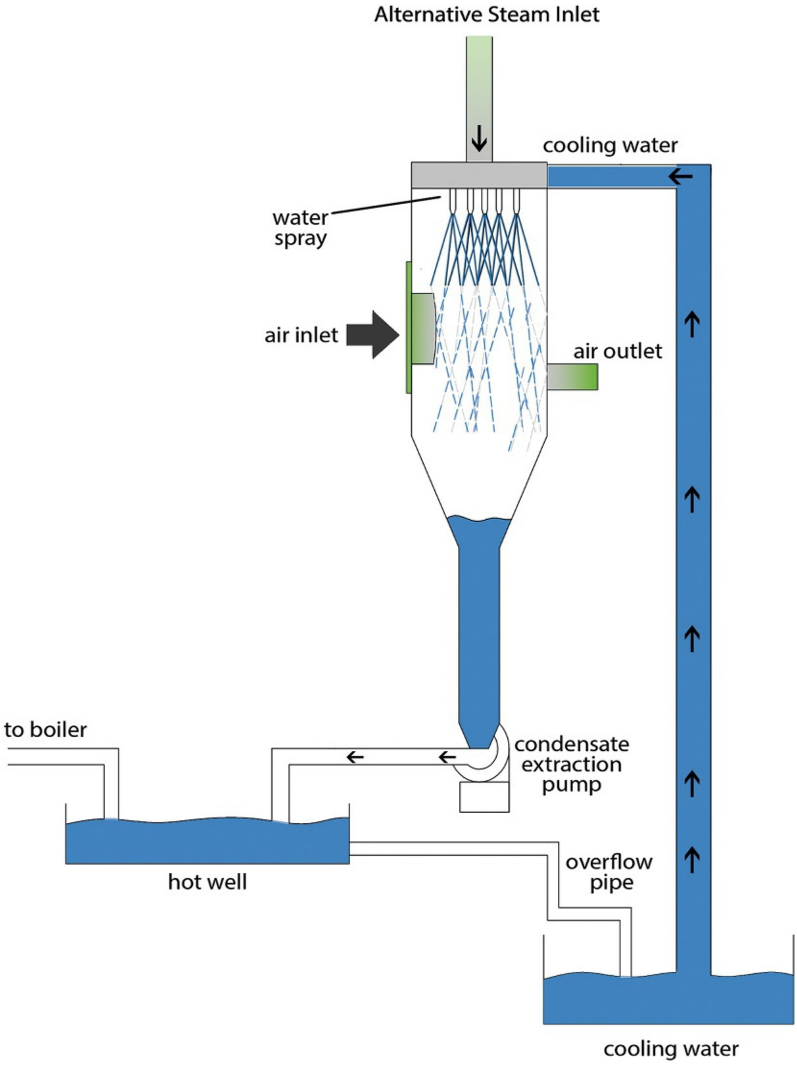

Fig. 7.2 Jet-type condenser.

7.3.1.4 Bubble- or pool-type condensers

In the bubble-type condenser, steam as a jet or bubble is injected into the continuous fluid or a pool of the cooling liquid. In the comparison of the three types of condensers mentioned above, their cooling water is injected into the chamber filled with vapor. The pool-type condenser is designed as a horizontal device. The vapor in the high-pressure injector enters the condenser under the action of the high-speed flow of liquid ammonia in the high-pressure ejector. Mixing, condensation, and possible chemical reaction could occur. The heat generated by the reaction or by gas-liquid condensation

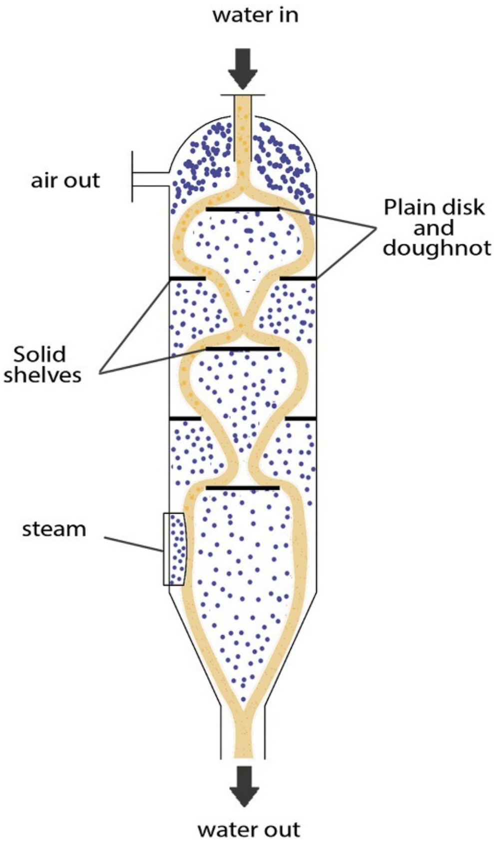

Fig. 7.3 Sheet-type condenser.

is absorbed by the steam condensate in the heat exchanger tube. Afterward, the low-pressure steam is produced, and it is used for the follow-up reheating, desorption, and vacuuming. The pool-type condenser is designed with a horizontal baffle, a vertical baffle, and a stripping gas distributor. After the vapor enters the bottom of the pool-type condenser, it is evenly distributed in the pool-type condenser through the distributor. This structure significantly increases the gas-liquid contact surface, and the incoming gas has a strong stirring effect in the continuous liquid phase, which improves the mass- and heat-transfer rate. Because the side of the pool-type condenser has a particular volume, the gas and liquid in this chamber are thoroughly mixed (Chan & Lee, 1982; Kakac, Liu, & Pramuanjaroenkij, 2012).

7.3.2 Evaporators

The evaporator is a kind of recuperative heat exchanger, which is an essential part of the four significant parts of refrigeration, including a compressor, a condenser, an expansion device, and an evaporator. The low-temperature condensed liquid passes through the evaporator to exchange heat with the outside air, where the gas absorbs heat to achieve the cooling effect. The medium to be cooled is usually water or air. For this reason, evaporators can be classified into two categories, evaporators for the cooling liquid, which is usually water or saltwater, and evaporators for cooling air. A common evaporator consists of a heating chamber, tubes, fins, a header, and an evaporative tank. The heating chamber offers the heat needed for evaporation to the liquid for boiling and vaporizing the liquid. The evaporative tank completely separates the gas and liquid phases. The vapor generated in the heating chamber has a large amount of liquid foam. After reaching the evaporative tank, these liquids can be separated from the vapor by self-condensation or by using a defoamer. The defoamer is usually located at the top of the evaporation chamber (Ribeiro Jr & Lage, 2005).

The header is a refrigerant distributor to make the refrigerant distributed in the pipes and placed between the expansion valve and the evaporator. The header is the larger pipe that connects to all circuits and supplies a specific amount of refrigerant to each circuit in the evaporator. The refrigerant flows inside the finned tube when air is released from the tube and fin surfaces. By increasing the total heat-transfer surface, the fin design improves the heat transfer from the gas in the evaporator pipes into the high-temperature refrigerant. The total heat-transfer surface of the evaporator is increased to increase the heat transfer from the air in the evaporator tube to the boiling refrigerant. Rectangular flat fin plates with the systematical arrangement are usually pierced by plenty of tubes or pipes an elliptical or circular cross-section (Huang, Xiao, Liu, & Wang, 2019). In the food industry, evaporators use heat to remove water from the foods, such as processed milk, vegetables, pastes, concentrates, coffee, fruit juices, and so on. The boiling point of the foods increases with concentration of the product. The quality of thermos-labile foods, such as juices and milk, can be maintained at low temperatures while the evaporation process occurs at low pressure. A variety of types of evaporators are applied in the food industry, such as natural circulation, rising-film, falling-film, batch-type, and agitated thin-film evaporators (Singh & Heldman, 2014).

The application of evaporation can be observed widely in various industries, such as the caustic chlorine industry, pulp, and paper production, phosphate industry, and food processing. During evaporation, solids and liquids are separated to recover solute from the solvent, usually the water. The unit operation of evaporation is similar to fractional distillation for the separation of the mixture with various volatile liquids. Vacuum evaporation is usually applied in single or multiple operations of each continuous stage. It can use the heat energy carried out from steam condensation in the previous stages. The advantage of multiple-stage evaporation includes the enhancement of process efficiency and the cost reduction of the operation in heat energy. The combination of low-temperature and high-vacuum techniques in the final stage of evaporation is used to dry the heat-liable product in the food and pharmaceutical industry. The main applications of the evaporation include air cooling in heating, ventilation, and air conditioning (HVAC) systems, heat rejection in spray ponds and cooling towers, the vapor production of flash evaporation in ocean thermal energy conversion (OTEC) and desalination, solute extraction, and petroleum distillation (Kreith & Boehm, 2013).

An evaporator with a direct contact heat transfer is also used in many types of industrial production. It mixes fuel (usually a gas and oil) with air and burns in a combustion chamber immersed in the solution. The high-temperature flame and flue generated are directly sprayed into the evaporated solution through a nozzle in the lower part of the combustion chamber. The high-temperature gas is in direct contact with the solution; heat transfer is carried out to evaporate and vaporize the water, and the generated water vapor and waste flue gas are discharged from the top of the evaporator together. The immersion depth of the combustion chamber in the solution is generally 0.2–0.6 m in some equipment, and the temperature of the gas exiting the combustion chamber can reach above 1000 °C. Because of the direct contact heat transfer, its heat transfer is highly effective, and the heat utilization is comparatively high. Because it does not require a fixed heat-transfer wall, the structure is simple, especially suitable for the evaporation of materials that are easy to be crystallized, are affected by scaling, and corrosive. It has been broadly used in the hazardous waste treatment of acid solutions and evaporation of ammonium sulfate solution. However, this type of evaporator is generally not applicable if the evaporated liquid is not allowed to be contaminated by the vaporized flue gas. Moreover, because of a large amount of flue gas, the utilization of secondary steam is limited. In addition, the nozzle is easily damaged because it is immersed in a high-temperature liquid (Kakac et al., 2012; Mori, 1991).

There are two basic designs of the direct contact evaporator with the immersed heating tank (Fig. 7.4) and with the external heating tank (Fig. 7.5). The water vapor production was enhanced with the initial droplet velocity in a single-stage system during the droplet evaporation. The size reduction of feed droplets significantly increased the droplet evaporation operation (Chen et al., 2016). Subsequently, a multistage model of direct contact spray evaporation and condensation system was reported in comparison with a single-stage system. A significant increase in water vapor production and thermal efficiency was displayed. For a 14-stage desalination plant, this technology has a better performance ratio of 6.5, which is defined as the ratio of equivalent heat of the distillate to heat input (Chen, Li, & Chua, 2016). A multistage low-temperature desalination system was powered with thermal 10 million watts concentrating solar power in cogeneration with thermal 7 million W diesel engines to desalinate 500 m^3 per day of fresh water. The cogeneration was predicted with the electrical power of 2.2 million W in the concentrating solar power plant to produce 520 m^3 per day of fresh water. Moreover, the output production would also be influenced by a variety of process parameters, including temperature, salinity load, and cogeneration fraction (Wellmann, Meyer-Kahlen, & Morosuk, 2018; Wellmann, Neuhäuser, Behrendt, & Lehmann, 2015).

7.3.3 Cooling towers

The cooling tower has been broadly used for decades as one of the major direct contact heat exchangers in a variety of industries, including crude oil refining and petrochemical operations, power stations, refrigeration, and air conditioning processes. In the cooling tower, water is used as a circulating coolant for absorbing heat from a system and discharging it into the environment to reduce the temperature of the loading hot

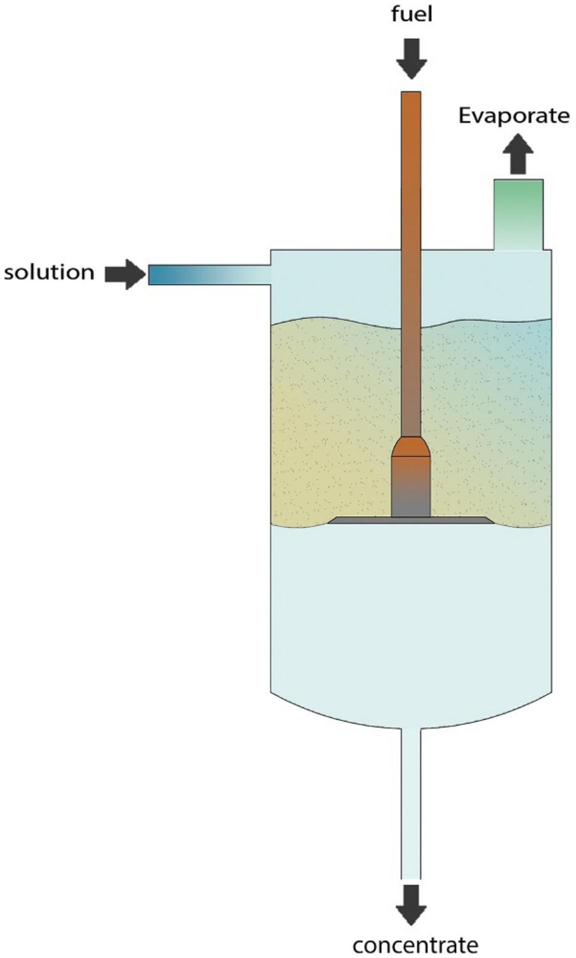

Fig. 7.4 Direct contact evaporator with the immersed heating tank.

water. The cooling tower uses water to directly contact air under heat exchanging, resulting in cooling down water and producing volatilized steam. The evaporation of steam takes away the heat to achieve heat dissipation. Besides, the convection and radiation of heat transfer disperse the waste heat generated in the industrial refrigeration and air conditioning to decrease the water temperature for maintaining the regular operation in the whole system (Naphon, 2005). The cooling tower can be classified into open (direct), closed (indirect), and hybrid circuit cooling towers (adiabatic cooling towers). In an open cooling tower, there is direct contact to decrease the water temperature with air. Direct heat transfer occurs during the interaction between discharged water and air. Besides, the evaporation with a small amount of cooled water makes the temperature of the cooling system decline (Lebrun & Silva, 2002; Milosavljevic & Heikkilä, 2001).

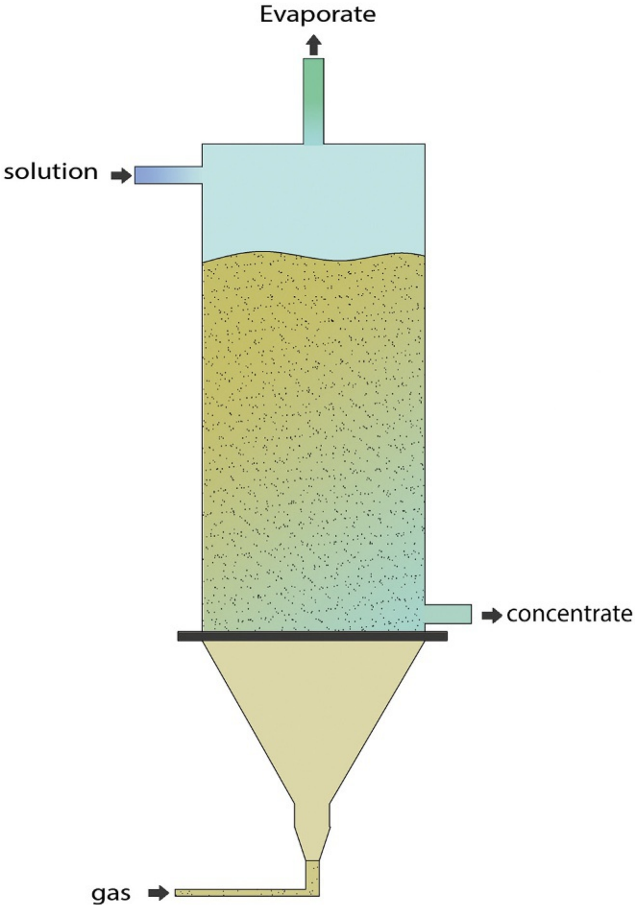

Fig. 7.5 Direct contact evaporator with the external heating tank.

7.3.3.1 Direct or open-circuit cooling towers

A direct or open-circuit cooling tower is a sealed structure with nozzles installed on the upper top of the cooling tower. The water that needs to be cooled down is introduced to these nozzles, and the circulating water is sprayed onto the packed bed full of glass fiber as the filler. It provides a large contact surface leading to the heat exchange effect achieved through water and air contact. The air circulation is introduced into the whole packed bed by a fan with blowing or extracting surrounding air. The fan drives the air circulation inside the tower to cool down the water by removing the heat with main evaporation and the convection between cool air and hot water. After heat exchange, the hot saturated humid air would be released from the tower to decrease the water temperature. The cooled water can be collected and recycled into the production process. The packed bed filling has multiple layers with a mainly vertical structure. The sprayed water or lateral splash water was spread for wetting the surface to create numerous small water droplets with a large surface area and several cascade layers of thin films (Lemouari, Boumaza, & Kaabi, 2009). In natural draft dry cooling towers, the performance of direct and indirect cooling for the heat rejection of a supercritical carbon dioxide Brayton cycle was evaluated. The comparison of direct and indirect cooled supercritical carbon dioxide Brayton cycles was estimated through a variety of ambient temperatures for concentrated solar power plants. In addition, the comparison of direct and indirect natural draft dry cooling towers in isolation was investigated through a range of input conditions (Duniam, Jahn, Hooman, Lu, & Veeraragavan, 2018; Hooman, 2010; Murray, 2009).

7.3.3.2 Indirect or closed-circuit cooling towers

In the indirect or closed-circuit cooling tower, direct contact is not involved between air and the water that needs to be cooled down. Nevertheless, an additional heat exchanger is used with piping and a plate heat exchanger. Unlike a direct cooling tower, there are two independent fluid circuits in an indirect cooling tower. One is that the water in the external circuit is in the secondary pathway, which is the hot fluid connected to the external loop of the tube bundle that is cooled and returned in a closed circuit. The air is driven through water circulation outside the entire heat pipe to provide a similar evaporative cooling. The heat flows from the internal fluid circuit, through the coil tube wall and the external circuit, and then heated by some evaporation of air and water into the ambient environment. In this process, the coolant is in a closed circuit, not directly exposed to external circulating water (Stabat & Marchio, 2004; Xia, Chen, & Wang, 2011).

7.3.3.3 Hybrid circuit or adiabatic cooling towers

The operation of the hybrid circuit or adiabatic cooling tower is similar to that of the dry cooling tower, except for the additional precooling pads inside the chamber of the adiabatic cooling tower. The adiabatic cooling system uses wet cooling but is equipped with a dry cooling unit. This design can use the environmental air to cool down the water temperature before entering the wet segment. Flowing water through precooling pads and then forcing air over the pads compress the dry bulb of the entering air to allow more extra heat rejection during operation. The major components of an adiabatic cooling tower contain a water basin, fan elements, dry cooling exchangers, cooling pads, mixing units, drift eliminators, a water distribution system, and a tower supporting structure (Shim, Sarker, Moon, Lee, & Yoon, 2010). The outside of the hybrid circuit cooling tower is usually made of different materials, including concrete, fiber-reinforced plastic, and stainless steel. Because consumption of water is decreased in the adiabatic system than in conventional evaporators, it can be used in high-temperature and low-moisture environments very efficiently.

Compared with dry condensers or coolers, the advantages of adiabatic systems include taking up a small amount of space for cooling ability and saving operative energy by reducing fan motor watt. Besides, the steam plume generated during operation is diminished by mixing the humid air from the wet segment and high-temperature air from the dry cooling unit. It can cause less potential icing visually in the atmosphere, especially favorable in the urban area or any surroundings close to the densely populated area (Sarker, Kim, Moon, & Yoon, 2008; Vitkovic, Storch, Puncochar, & Stodulka, 2016).

7.3.4 Flash evaporators

When high-pressure saturated water enters a relatively low-pressure container, the saturated water becomes part of the saturated steam and saturated water under the container's pressure owing to the abrupt reduction in pressure. The major use of flash evaporation is the recovery of boiler drainage in thermal power plants and geothermal power generation. The flash tank's primary role is to allow the higher-pressure stream to enter into the lower-pressure tank, depressurize the high-pressure stream, and evaporate the lower-boiling point components in the stream to accomplish the effect of separation. The water recovery of boiler drainage in thermal power plants and geothermal power generation is the major usage of flash evaporation. The primary function of a flash evaporator is to transfer the higher-pressure stream into the lower-pressure tank, where it is rapidly depressurized. The components in the stream with lower boiling points are evaporated to accomplish the effect of separation. A flashing jet with rapid phase alteration might result from an inadvertent leak of pressurized liquid from supply pipelines or liquid storage containers. This quick phase transition can result in a rapid combination with an oxidant such as air. It can cause severe consequences such as explosions, causing damage to industrial equipment while the liquid is flammable.

Besides, the advantage of flash evaporation in industrial applications has the potential to have a significant impact on the performance of a variety of devices, such as injectors and reactors (Mansour & Müller, 2019). Heat transport data are supplied for direct contact evaporator and condenser designs suited for open-cycle ocean thermal energy conversion (OC-OTEC) applications. Under normal operational circumstances, falling turbulent jets and films were evaluated. Because of the breaking of the jets (or films) into sprays, the flash evaporator performance was rather consistent over the range of circumstances tested, with efficiencies as high as 95%. The Reynolds number of the jet and the steam air content has an impact on condenser performance. Jets produced a condenser heat-transfer coefficient of 27 kW/m^2 °C, which was greater than those recorded with films. After it was demonstrated that none of the existing correlations discovered in the literature could correlate all of the data patterns detected, an empirical correlation was established for the condenser data (Sam & Patel, 1984). A conventional flash distillation system indicated that the significant single component of capital cost and thermodynamic irreversibility is related to the transfer of heat from condensing steam via tubes into the brine. The heat energy available in flashing brine is used to raise brine against gravity. A vertical configuration allows gravity to be utilized to force brine to flow through a countercurrent heat-transfer system employing direct contact with a fluid. In addition, the work done may be favorably used as potential energy for pumping. Experiments on vertical flashing brine flow and direct contact heat transfer are presented. Besides, the theoretical design approaches were considered for both fluid and metallic heat-transfer surfaces (Walker, Newson, & Johnson, 1967).

The direct contact spray flash evaporation and condensation systems have been studied for many years (Alrowais et al., 2020). For the prediction of distillate production during spray flash evaporation, a superheated water jet was driven by nozzles into a cooling tank where the feed temperatures were between 40 and 80 °C to determine empirical equations (Miyatake, Tomimura, Ide, & Fujii, 1981; Miyatake, Tomimura, Ide, Yuda, & Fujii, 1981). The flash evaporation performance on saline water was estimated. Both computational and experimental approaches were used at vacuum pressures less than 2.40 kPa and low feed temperatures from 26 to 32 K (Muthunayagam, Ramamurthi, & Paden, 2005). Based on experimental results of upward jet flash evaporation, a comparison analysis of a spray flash desalination method with the injection direction is determined. The superheated stream at 24.0, 30.0, and 40.0°C was pumped upward into a depressurized container over a stainless-steel cylinder nozzle to compare the occurrences of a downward jet flash evaporation technique. A series of tests were performed to estimate the influence of injection direction on the spray flash evaporation (Ikegami, Sasaki, Gouda, & Uehara, 2006). The flash evaporation system containing upward jets with larger nozzles was also studied. The results showed that the power of operation in the flash evaporation system could be enhanced with the superheat stream's degree and initial liquid temperature (Mutair & Ikegami, 2009, 2010). The flashing operation using tap water at various flow rates was demonstrated with the inlet fluid temperature between 40 and 70°C. Meanwhile, the pressure of stream injection was 6 bar, and the temperature of superheated fluid was from 6 to 18 K. The results indicated that the production of water steam and the efficiency of the flash process are inversely proportional to the tank size (El-Fiqi, Ali, El-Dessouky, Fath, & El-Hefni, 2007).

7.3.5 Scrubbers

The scrubber is widely used in various industries to clean and purify the gas vapor for different purposes, such as using a liquid to absorb specific components in the gas mixture, removing dust from the gas, humidifying or drying the gas, and so on. Industrial scrubbers are used to improve air quality by removing contaminant particles and harmful dust in gases from industrial exhaust streams to maintain air quality. They can also protect employers and their employees from combustion and provide a safe and healthy working environment. Therefore, the scrubber plays an important role in air pollution control devices (APCDs). In 1858, the first version of an air scrubber was designed and developed in Spain by Spanish engineer Narcís Monturiol i Estarriol. It was built to remove carbon dioxide from the submarine by driving the air through a vessel of calcium hydroxide to allow the submarine to *stay* and operate underwater for a very long time.

The process of direct contact heat transfer occurs between cold water and hot flue gases in scrubbers. Both substances under different temperatures have heat exchange to initiate the interaction of molecules by heat conduction on the basis of a temperature gradient. The efficiency of heat recovery from flue gases in scrubbers is influenced by convection, condensation, evaporation, and heat conduction during heat and mass transfer (Blumberga et al., 2020). A total of more than 15 variable factors are involved in these heat recovery processes (Cao, 2010). According to the methods of scrubbing pollutants out of the exhaust, the industrial scrubbers are classified into three major types—wet scrubber, semidry scrubber, and dry scrubber.

The wet scrubber is particularly used to treat the water-soluble pollutants in the exhaust gas as shown in Fig. 7.6. The coarse dust and specific pollutants in the fuel gas can be removed by spraying a chemical liquid through the gas. The exhaust gas flows into the packing layer in the tower. The exhaust gas and the scrubbing liquid produce a chemical absorption reaction in the packing layer, which can effectively control the volatile organic compounds, sulfuric acid, hydrochloric acid, hydrofluoric acid, nitric acid, and ammonia contained in the exhaust gas, because they are soluble compounds in water solution. Direct heat transfer between the gas bubbles and their surrounding scrubbing liquid results in several correlations for the heat-transfer coefficient and free convection between gas bubbles and liquids. The wet scrubber has the advantages of low initial cost, easy maintenance, and simple operation (Abdulwahid, Situ, Brown, & Lin, 2020). In some wet scrubbing methods, the combusted flue gas is first treated by heat recovery before being passed into the scrubber. The aqueous solution with the adsorbent is sprayed into the scrubber to contact the organic exhaust gas, and the gas is dissolved into the liquid phase through diffusion. The chemical reaction with the absorbent in the liquid phase can achieve the purpose of waste removal. The final product is removed from the bottom of the tower. Because the final discharged substance contains high moisture, it is called the wet scrubbing method.

On the other hand, semidry scrubbing is also called spray scrubbing. The theory is similar to that of the wet scrubbing method. The difference is that the water content in the final exhaust materials is reduced, and the droplets are completely removed inside the chamber. As a result, the final product is in dry powder form, and the granular collector can gather it in the latter stage to remove the pollutant gas (Fan, Yang, & Yuan, 2009). The dry scrubbing method is to pass the exhaust gas through the packed bed containing a solid adsorbent. The toxicity of the exhaust gas is removed by adsorption reaction. Solid adsorbents mainly include activated carbon, activated aluminum oxide, zeolite, and so on. The dry scrubbing does not produce secondary wastewater, has simple design, can be easily maintained, has a low cost, and does not require additional energy. Besides, their adsorption material can be regenerated after saturation, and a high removal efficiency for toxic gases can be provided. Based on the above advantages, many enterprises use dry scrubbers to deal with the problem of toxic gas emissions (Wang, Taricska, Hung, Eldridge, & Li, 2004).

7.4 Phase characteristics of the contacting fluids

This section will mention various direct heat exchangers based on their phase characteristics of the contacting fluids. Immiscible fluid, gas-liquid, liquid-liquid, and liquid-vapor heat exchangers will be discussed.

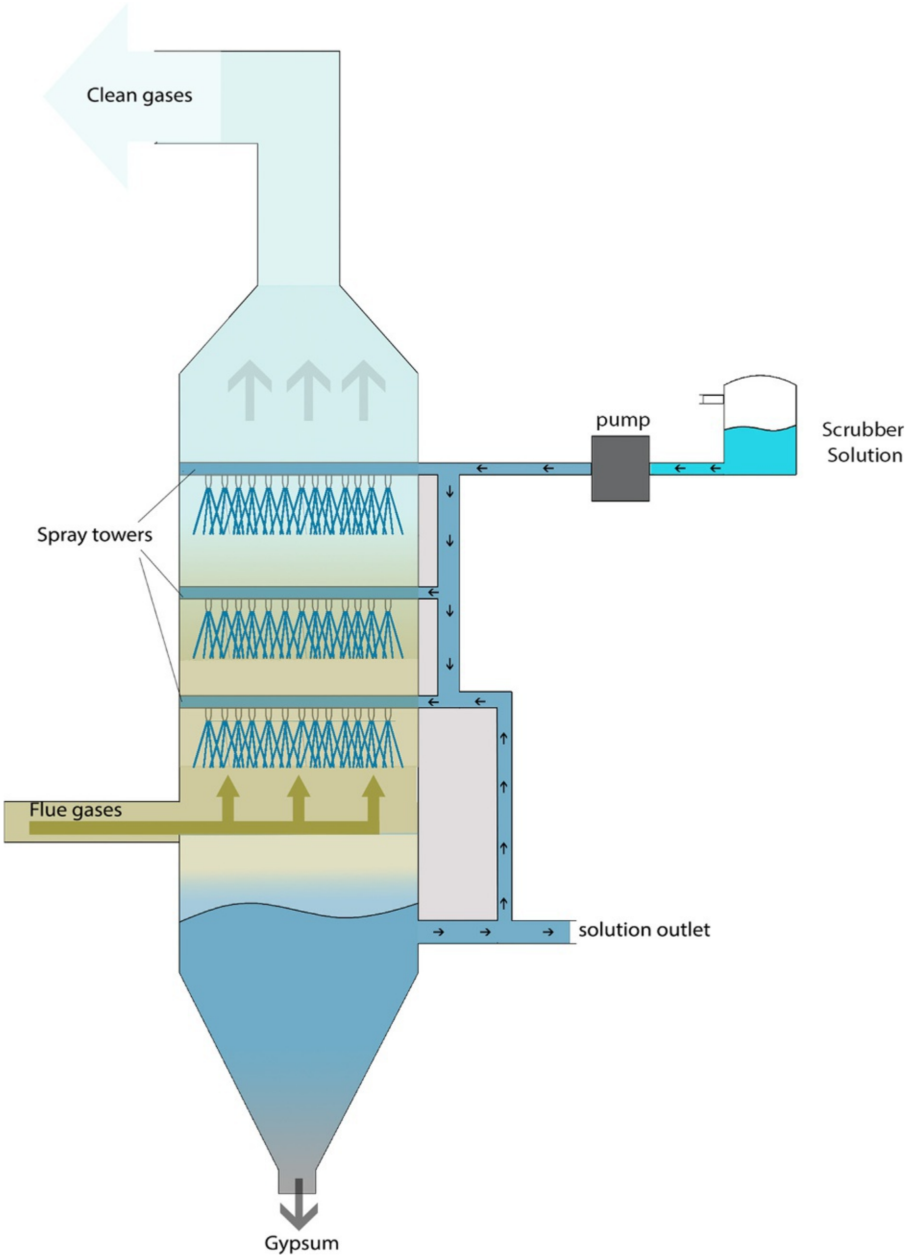

Fig. 7.6 Wet scrubber.

7.4.1 Immiscible fluid heat exchangers

There is direct contact between two immiscible fluids in the immiscible fluid exchanger, and this type of heat transfer has been studied for decades. Both dispersed and continuous streams provide scientific and practical significance in the fundamental properties of heat transfer. The single-phase or multiphase fluids may be used in evaporation or condensation during processing. The typical examples are oil vapors and organic vapors condensing with water or air (Prakash, 1966; Shah & Sekulic, 2003). Understanding heat-transfer processes between drops and continuous fluids and precise prediction of transfer coefficients for a particular system have developed well in decades.

Nonetheless, the prior experience can offer a hint at the transfer mechanism to be encountered, allowing the required coefficients to be estimated. In the water desalination process, the benefits of direct contact heat transfer with metallic transfer surfaces have been studied and utilized for decades. The heat-transfer mechanism is complicated when drops enter a constant variable temperature field and a constant-temperature field. Through a simultaneous phase transition, heat is transmitted to droplets and bubbles. The entirely mixed drop, the drop with internal circulation, and the rigid drop are the three models considered when addressing a constant-temperature field. With a simultaneous phase transition, heat is transmitted to droplets and bubbles. When addressing a constant-temperature field, three models are considered: stiff drop, entirely mixed drop, and drop with internal circulation. Low-cost, efficient water desalination devices and equipment are widely used in the principle of direct heat exchangers. Multiphase heat transfer is involved in latent heat exchanging across immiscible fluids. This multiphase exchanger has been successfully employed in direct contact freezing elements where a disseminated volatile fluid evaporates in saline water while a portion of the water freezes simultaneously (Marschewski & Stojunoff, 1983; Sideman, 1966).

Heat exchanging between two immiscible fluid phases in turbulent flow is important because this type of heating system can improve the compactness, residence time, and energy cost. The high-efficiency vortex unit employed as a direct contact heat exchanger is a general multifunctional exchanger/reactor in which wall tabs create longitudinal vortices that increase phase dispersion, macromixing, and rapid temperature uniformity in a turbulent flow. The experimental thermal data in the direct-contact heat exchanger are used to verify an algebraic one-dimensional thermal model that accounts for the axial evolution of phase temperatures associated with drop breakup. This model needs to understand the turbulent flow under single-phase circumstances to apply to various flow geometries for engineering design. Regardless of the phase separation at the output, the direct contact heat exchanger has a higher global Nusselt number than a double-jacketed heat exchanger. Besides, the heat transfer of a high-efficiency vortex requires less energy than the other direct contact heat exchangers with the same capacity of heat exchanging (Lemenand, Durandal, Della Valle, & Peerhossaini, 2010).

7.4.2 Gas-liquid heat exchangers

There is direct contact heat transfer between the gas and a low-pressure liquid in a gas-liquid exchanger, where the gas and liquid are usually air and water. Partial liquid evaporation and vapor removal by the gas occur in the operation of water cooling and air humidification. Because of the evaporation of the liquid, mass transfer accounts for most of the energy transfer in these exchangers, with convective heat transfer being a minor factor that takes less than 10% of total energy transfer. The application of gas-liquid exchangers can be found in a variety of industrial units, such as cooling towers with forced- or natural-draft ventilation, spray dryers or ponds, and air-conditioning spray vessels (Shah & Sekulic, 2003). The energy and mass-transfer coefficients in the gas-liquid phase and the relationship of interfacial layers are exhibited in various devices, such as packed columns in co- and countercurrent flow, packed bubble columns, plate columns with bubble cap and sieve trays, stirred tanks, spray towers, and bubble columns (Charpentier, 1981).

Energy may be recovered from hot gas discharge streams by transferring it straight to a coolant liquid in one of many gas-liquid direct contact units. The heat energy may be used in the evaporation of a Rankine cycle fluid or in a fluid stream during the process of petroleum and chemical reaction. Heat exchangers with direct gas-liquid contact are built along the same tube to gas absorbers. The diameter of tubes should be wide enough to avoid excessive entrapment of the liquid in a flowing gas and flooding. Based on the design of the direct contact unit, the maximum velocity of the fluid stream varies. The dimensions of the heat exchanger should allow the appropriate temperature to be reached between the entering water and the discharged air. Many designs of direct contact devices include sprays, trays, structured packing, and random packing used as in gas absorbers (Fair, 1990).

The heat-transfer coefficient in a packed column was estimated for the nonvolatile oil or cooling water. Mass and energy transfer of the gas-liquid packed column shows a high efficiency in distillation, fascination, and shedding. A number of applications of packed columns use the direct contact between the gas and liquid phases to achieve heat exchanging effectively. Meanwhile, the mass transfer also occurs simultaneously. The process applications are the consequence of the direct contacting mode's uncomplicatedness and low cost and the challenges with surface fouling that may be expected in shell-and-tube equipment. While the methods for estimating pressure drop and flooding are similar to those used in mass-transfer applications such as distillation and gas absorption, both need empirical methodologies. The methods for predicting heat-transfer rates were studied and developed (Huang & Fair, 1989).

The gas-liquid heat exchanger involving energy-efficient polymers was studied. The compression process used on offshore platforms to liquefy natural gas creates more heat commonly dispersed using seawater-cooled plate heat exchangers. Gasket plate heat exchangers are widely used as pasteurization units in the food industry to deactivate microorganisms for foodborne illness prevention (Lee, Chen, & Frank, 2015). A conductive polymer packed with a carbon fiber thermally was examined for the possibility of using commercially available material to improve thermal conductivity by order of magnitude or more. According to the research, the total coefficient of performance is roughly twice that of aluminum, and a total coefficient 10 times that of titanium might be reached. A thermally improved polymer heat exchanger uses 70% of its total lifetime energy in manufacturing, compared to 97% and 85% for titanium and aluminum heat exchangers, respectively. In terms of thermal performance and life cycle energy consumption, the study revealed the advantages of thermally enhanced polymer heat exchangers over traditional ones (Luckow, Bar-Cohen, Rodgers, & Cevallos, 2010).

7.4.3 Liquid-liquid heat exchangers

The heat transfer in the liquid-liquid heat exchangers occurs in a heat-transfer plate or from a liquid loop to another fluid stream. A heat exchanger is integrated to enhance the liquid's surface area for rejecting or absorbing heat and transporting it to a secondary fluid stream. The heat load is transported from the drive to the heat exchanger through the drive loop. The supply loop collects the heat load and delivers it to the user's cooling system liquid source through the heat exchanger. The user is responsible for using and selecting a heat load disposal system (Abu-Hamdeh, 2002; Bar-Cohen, Rodgers, & Cevallos, 2008; Omelchuk, Stambouli, & Chagnes, 2018). The phase of the working fluid, the type and size of the contactor, and operating circumstances are all critical considerations in designing an industrial liquid-liquid process. The end product is inexpensive in thermal operations where the liquid-liquid contactor is utilized for heating or cooling, such as in desalination or power plants. Equipment and operating costs must be kept to a minimum in such procedures. It is important to keep the equipment clean and free of particles on the heat-transfer surfaces. However, the fundamental problem in such systems is the working fluid losses induced by dissolution and entrainment. The device is intended to prevent entrainment, and insoluble organic solutions are used to reduce dissolving. In other thermal procedures, one of the liquids is used to heat or cool the other liquid to alter precipitation, dissolution, or reaction. The primary goal may be the product's qualities rather than the cheapest contacting liquids or the simplest equipment. Extraction techniques are examined in the same way. The characteristics of a more costly product may require a more soluble contacting liquid or a smaller contactor. Solvent losses and recovery costs as well as equipment maintenance may be acceptable in such operations. Besides, the availability of a low-cost insoluble solvent and simple equipment may lead to the deployment of extraction techniques that would be overlooked (Letan, 1988).

7.4.4 Liquid-vapor heat exchangers

Direct contact heat transfer between two immiscible liquids has been applied in many industrial operations, including water desalination (Snyder & Spiegler, 1966), crystallization (Byrd & Mulligan, 1986; Tao, Chunxiang, & Ziqiu, 1997), and solar and geothermal power (Jacobs, 1988). This design provides many advantages, including less scaling and fouling issues, a relatively simple structure, and a higher heat-transfer coefficient, which is 20–100 times more than the single-phase stream, no corrosion occurring in metallic heat-transfer surfaces, and operation at relatively small thermodynamic driving forces. The heat transfer with a gas-liquid-liquid three-phase system in a direct-contact parallel flow exchanger was studied. The influence of operational factors on the volumetric heat-transfer coefficient was also investigated and developed. The evaporation of the continuous phase fluid into the dispersed phase, possible coalescence, and break-up of the two-phase droplets were evaluated (Peng, Yiping, Cuili, & Kun, 2001).

Evaporation and condensation in well-designed heat exchangers can obtain significantly high heat-transfer coefficients to improve liquid-vapor heat exchange. A two-phase stream is operated in the enhanced surface. In addition, evaporation and condensation in channel geometries are exhibited along with correlations. The design correlations for predicting two-phase pressure loss are presented in these surfaces, including offset strip fin, perforated fin, and plate-fin geometries and tubes with twisted-tape inserts as well as ribbed or grooved walls. Last, the designs of evaporators and condensers were developed and exhibited (Carey & Shah, 1988). The heat exchangers in pasteurization use heat at high temperature in a moist environment for microorganism inhibition instead of using chemicals (Lee, Chen, & Frank, 2016).

The liquid-vapor heat exchangers are commonly found in condensation or evaporation units. With direct contact between two phases, the waste stream can usually heat up water or steam condensed by cooling water. The remaining noncondensable steam and hot water are released in the discharged stream. A deaerator and an open direct contact feed water heater in many power plants are two-phase types of heat exchangers. Furthermore, the desuperheating system also uses liquid-vapor heat transfer with direct contact to restore superheated steam to its saturated condition or lower the superheated temperature (Jacobs, 1988).

The direct contact heat exchanger with three-phase vapor-liquid-liquid is designed and developed in recent years. Its volumetric heat-transfer coefficient with direct contact in a three-phase condenser was investigated. Although the heat-transfer coefficient increased, the continuous phase mass flow rate and the holdup ratio also increased. Besides, the optimal value of the continuous phase mass flow rate increased when the vapor dispersed phase mass flow rate was also enhanced. Nevertheless, the temperature obtained by the continuous phase has a significant influence (Mahood, Campbell, Thorpe, & Sharif, 2018).

7.5 Conclusion

Direct heat transfer is usually considered heat transfer from one fluid to the other fluid directly without intervening plate-like or sheet-like walls. Direct heat transfer may occur between two or more mass fluids, which can be concurrent flow (parallel flow), counter flow, and even cross flow. In addition, these fluids can be miscible, immiscible, partly miscible, and partly immiscible. According to the phase characteristics of the contacting fluids, direct heat transfer between the two fluids includes solid-gas, gas-liquid, liquid-vapor, liquid-liquid, immiscible fluid, and even solid-solid. For the typical heat exchanging system, the liquid is commonly water or sometimes an organic chemical solution. The gas is usually air or steam during the heat-transfer process.

One of the main challenges of designing an effective heat conversion system is that efficient heat transfer at a specific temperature is capable of maximizing the potential of the heat source thermodynamically in the designated system. In a conventional heat exchanger, heat transfer occurs between the hot and cold streams in the heating surface. Therefore, the maximum potential of thermodynamic ability in a conventional heat exchanger is restrained because of built-in energy losses of the intervening solid heating surface that divides two different fluid streams. According to this type of design, the heat-transfer efficiency has degenerated significantly because the heat-transfer coefficients decrease over time. It is caused by the accumulation of undesirable materials deposits on heating surfaces for the duration of the heating and cooling process. The fouling is found among most industrial heat exchangers to influence the heat-transfer effectiveness, fluid resistance, and pressure decline. Under thermal processing, high temperature leads to a variety of deteriorations on the wall of the heating surface by corrosion regardless of the two-fluid steams between gases, liquids, vapors, and solids. In the direct heating system, two fluid streams are allowed to contact directly in order to alter the final temperature in the materials. On the other hand, the indirect heating system utilizes conduction, convection, or radiation to reach energy balance instead of involving any form of contact and exposure between solids, liquids, gases, or any other type of media. The application of direct heat exchangers can be predicted to develop rapidly in a variety of industries because of all the advantages discussed in this chapter.

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