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School of Energy Systems
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Master's Thesis

DESIGN RULES FOR STEAM CONDENSATE SYSTEMS

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ABSTRACT

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Design rules for steam condensate systems

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This master's thesis focuses on the design of steam condensate system of steam power plants. Condensate is generated when fractions of extracted steam from the turbine transfer heat to feedwater in the feedwater heaters. Also small amounts of condensate form in steam pipelines due to radiation heat loss. The condensate produced in the steam using equipment and pipelines should be removed as quickly as possible in order to avoid various problems, such as fractures in pipeline fittings, loss of live steam and so forth. The recovered condensate is treated water containing sensible heat that accounts for approximately 10% to 30% of the total heat contained by the live steam. Thus the boiler fuel demand can be potentially reduced from 10% to 20% by economically recovering hot condensate. The proper design of condensate system requires detail knowledge about condensate piping network, different components of the system as well as various problems associated with condensate flow both in steam and condensate pipelines. In this study, major components of steam condensate system are presented, followed by a discussion of most common problems with condensate, such as water hammer, flash steam, pipe erosion and so on. For optimum design of steam condensate system, the study highlights recommendations for the slope of horizontal steam and condensate pipelines, analysis of condensate flow behaviour in upward inclined steam pipes, sizing of components, such as drain pockets, discharge lines from steam traps, and the importance of using different components in steam condensate system.

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Akhtar Zeb
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

BR	Branch
CFV	Condenser Flash Vessel
CHV	Check Valve
CO_2	Carbon dioxide
d_1	Drain pocket diameter
d_2	Depth or length of drain pocket
D	Steam main diameter
Elev	Elevation of pipe (m)
fG	Steam mass flow rate (kg/s)
fL	Condensate mass flow rate (kg/s)
FWHs	Feedwater heaters
h_f	Liquid enthalpy (kJ/kg)
h_{fg}	Enthalpy of evaporation (kJ/kg)
HE	Heat Exchanger
HEI	Heat Exchanger Institute
HP	High Pressure
IP	Intermediate Pressure
L	Length of the pipe between anchors (m)
LP	Low Pressure
NO_x	Nitrogen oxides
NPSH	Net Positive Suction Head
PIP	Pipe
PO	Point
P_1	Higher-pressure (bar)
P_2	Lower-pressure (bar)
s	Entropy
SO_x	Sulphur oxides
α	Expansion coefficient (mm/m °C × 10^{-3}), Void fraction (-)
ΔT	Temperature difference between ambient and operating temperatures (°C)

1 INTRODUCTION

Steam is produced by combusting fuel in the boiler of a steam power plant. The superheated steam is expanded to a lower pressure in the turbine generating mechanical work energy of a turbine shaft rotation, which in turn when connected to a generator produces electricity. The steam exiting the turbine is directed towards the condenser where it changes into condensate by losing the heat of evaporation to the cooling system. Condensate also results from fractions of extracted steam from the turbine which are used to heat up feedwater in the feedwater heaters, the process is called regeneration and improves plant efficiency. The condensate produced is either cascaded backward to the condenser hotwell or pumped forward to the deaerator for removing non-condensable gases and further heating. Furthermore, small amounts of condensate form in steam pipelines due to radiation heat loss.

Saturated water changes into dry saturated steam by absorbing latent heat (enthalpy or heat of evaporation) in the boiler and by releasing this heat steam changes back into the high-temperature high-pressure saturated water, which is commonly known as condensate. The heat released by the steam during condensation process is utilized to heat up the incoming liquid, process or equipment, depending on the desired requirement. The hot condensate formed is treated water containing sensible heat because during phase transition the temperature and pressure do not change and should be recovered for reuse as it accounts for approximately 10% to 30% of the total heat contained by the live steam. Therefore, the boiler fuel demand could be reduced from 10% to 20% by economically recovering hot condensate.

The accumulation of condensate in steam, as well as condensate pipelines, is not free of problems. The presence of condensate in steam pipelines causes water hammer which is noticed by the noise and displacement of pipes it produces. Water hammer reduces the life of pipework equipment, produces fractures in pipeline fittings, and causes loss of live steam from steam pipelines. Similarly, condensate changes into flash steam in condensate pipelines due to pressure differences. Flash steam results in huge velocities in the pipelines and formation of vapour clouds that deteriorates the working environment.

Thus the proper operation of steam condensate system is crucial for the performance of a steam power plant as it increases the plant efficiency and economics by reducing the boiler heat demand, the failure rate of pipeline equipment and environmental hazards.

Steam power plant engineers usually concentrate on steam supply and the heat it provides to feedwater for improving plant efficiency and reliability by addressing various problems, such as piping leaks, steam trap leaks and insulation. They overlook the importance of steam condensate system unless significant issues already exist, such as water hammer, high back pressure, and pipe damages. Hence, to achieve higher productivity, energy efficiency, and site reliability, the design of steam condensate system should be given equal attention.

Condensate systems of steam power plants comprised of several components and pipelines, the detail design of which requires an engineering team having expertise in different areas, such as piping design, pumps, valves, steam traps, flash vessels, and so forth. It is not easy to cover all those features in the present work. However, in this study, some of the most important design parameters and recommendations from the specialists dealing with the design and operation of steam condensate systems are presented.

This master's thesis work has been divided into eight sections. Section 1 is an introductory part highlighting the role of steam condensate system in enhancing the efficiency and economics of steam power plants. The distribution of work among the sections 2 to 8 are described as under.

- Section 2 introduces the main components of steam power plants, followed by Rankine cycle which is a vapour-and-liquid cycle and accepted as the standard for steam power plants. The ideal Rankine cycle, as well as triple extraction regeneration cycle, are discussed. The three types of feedwater heaters are also briefly presented.
- Section 3 explains what condensate is and where it generates in steam power plants. The benefits of condensate recovery are listed. Also the layout and condensate flow directions of a typical condensate system of steam power plant are shown.
- Section 4 deals with the major components of steam condensate system. Working principles of the three main types of steam traps, namely mechanical, thermostatic and thermodynamic steam traps, are explained. The topics of pumps and valves are shortly introduced. The importance of strainers, used to remove dirt and debris from steam and condensate, in steam condensate system is highlighted. The extraction steam system, heater drains and vents systems, and condensate dump systems are discussed.

- Section 5 covers some of the main problems associated with condensate flow in the system. The potential damages caused by water hammer and flash steam generation in the steam and condensate pipelines are considered. The adverse effects of air and other non-condensable gases on the performance of condensate and feedwater heating systems are discussed. The problems of stall and corrosion & erosion of steam and condensate pipelines are also presented.
- Section 6 presents important design considerations necessary for the optimum design of steam condensate systems. The efficiency and cost of the three different configurations of condensate pipelines are compared. The slope for both horizontal steam and condensate pipelines are discussed. Sizing of drain pockets, discharge lines from steam traps and pumped condensate lines are explained. The significance of using flash vessels, eccentric reducers, expansion allowance for hot steam and condensate pipelines, length of rising condensate lines, length of drain lines to steam traps and taking branch line connections from the top of steam mains is recognized. The section mainly focusses on the recommendations of the specialists dealing with the design and operation of steam condensate systems.
- Section 7 analyses the two-phase (steam-condensate) flow in upward inclined steam pipes. When there is no steam flow, the condensate moves downward in such pipes due to gravity. However, at certain minimum steam flow rate (steam velocity) the condensate starts flowing cocurrently with steam in upward inclined steam pipe. This minimum steam velocity depends on many factors. The effects of pipe length, flow area, elevation and pressure & temperature gradients are examined.
- Section 8 summarises the study and discusses the future work on the topic of steam condensate system in steam power plants.

2 STEAM POWER PLANTS

Steam power plants convert heat energy from the combustion of a fuel into mechanical work energy of a turbine shaft rotation. The main components of a fossil fuelled steam power plant are shown in Figure 1. The plant has been divided into four subsystems identified by the letters A through D. In the subsystem A, energy is supplied to vaporize the working fluid (water) into vapour (steam) which is then directed towards the turbine of subsystem B. The steam is allowed to expand to a lower pressure in the turbine, producing mechanical power. The shaft of the turbine when coupled with an electric generator (subsystem C) transforms the mechanical power of the turbine shaft into electric power. After expanding through the turbine, the steam is condensed in the condenser by releasing heat to the cooling system. The subsystem D provides the cooling water circuit. The cooling water (warm water) is transferred to the cooling tower where it releases the absorbed heat from the steam to the atmosphere. The cooling water (cooled water + makeup water) is then pumped back to the condenser for condensing steam and the condensate is pumped to the boiler for steam generation (subsystem A), and the cycle is repeated.

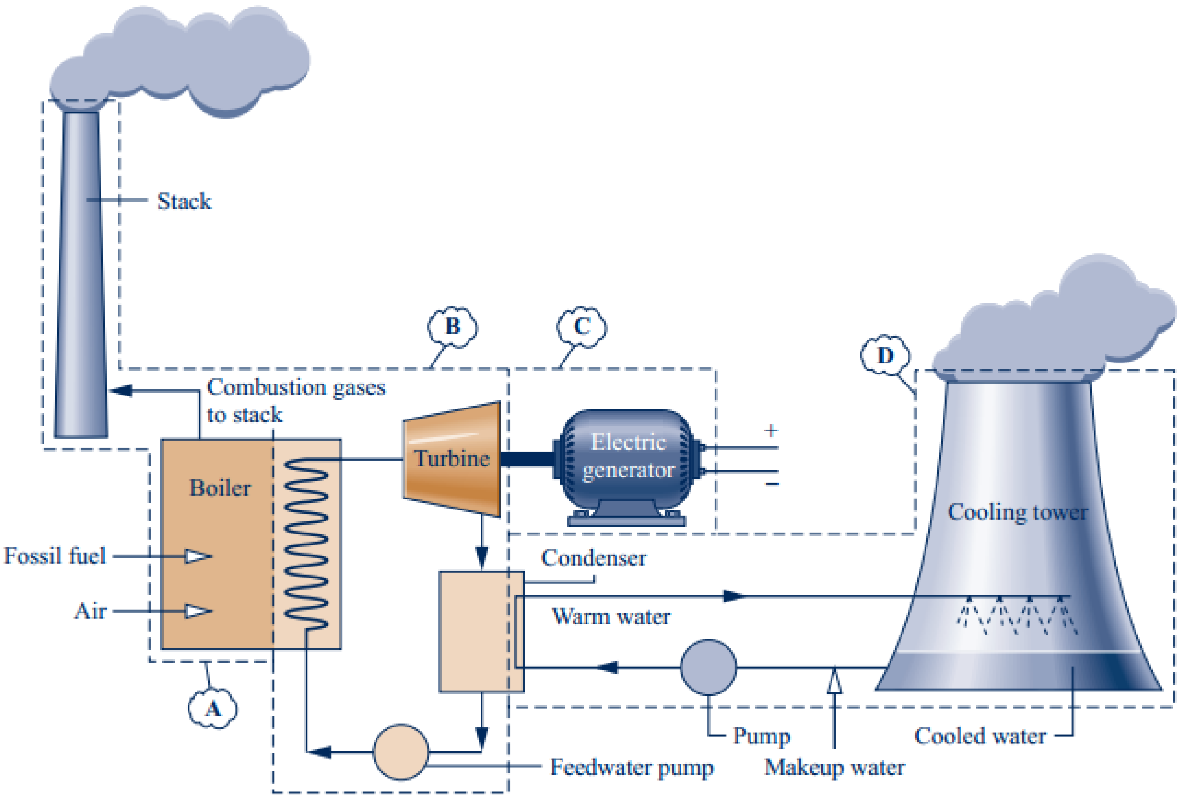


Figure 1. Main components of a fossil fuelled steam power plant (Moran, et al., 2011)

2.1 The steam cycle

Rankine cycle is a vapour-and-liquid cycle and accepted as the standard for steam power plants. The real Rankine cycle utilized for electricity generation is quite complex and is not the focus of this study. Here the simplest ideal Rankine cycle is presented in order to understand different processes involved in a steam cycle. Figure 2 shows the processes of an ideal Rankine cycle on the temperature-entropy (T-s) diagram. The saturated Rankine cycle 1-2-3-4 represents the conditions when there are no irreversibilities in the cycle, no frictional pressure drops in the boiler & condenser and the processes through the turbine & pump are isentropic (constant entropy). The processes undergo by the working fluid are:

- **Process 1-2 -** The working fluid as saturated vapour (dry saturated steam) at state 1 expands isentropically through the turbine to the condenser pressure
- **Process 2-3 -** The working fluid losses heat at constant pressure and temperature in the condenser and changes into saturated liquid (water or condensate) at state 3
- **Process 3-4 -** The saturated liquid at state 3 is compressed in the pump isentropically to state 4, increasing pressure of the working fluid to the boiler pressure
- **Process 4-1 -** The working fluid is heated in the boiler at constant pressure up to state 1 (dry saturated steam) to complete the cycle

The superheat Rankine cycle 1′-2′-3-4 shows the superheating of the working fluid beyond state 1. The process of superheating results in increased plant output and efficiency. Also, the processes of reheat and regeneration feedwater heating are employed for the better performance of steam power plants. The process of regeneration is explained below.

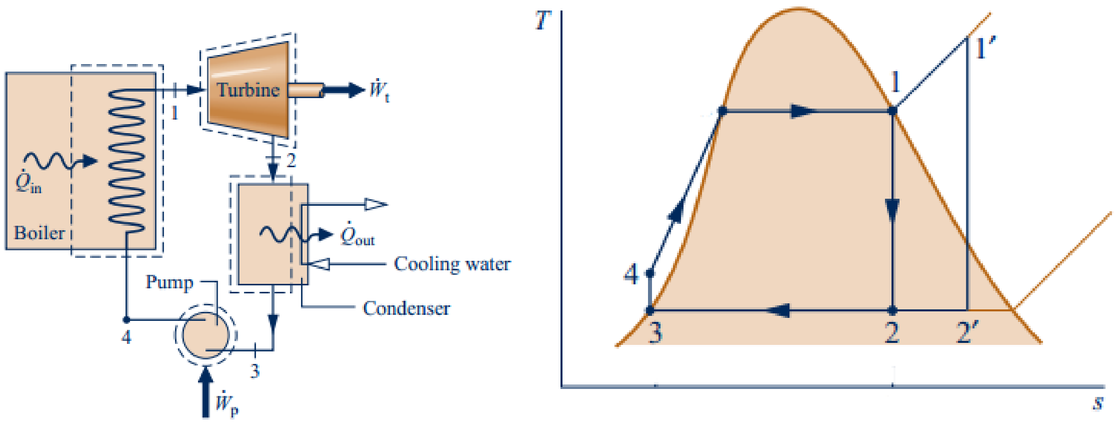


Figure 2. Working principle and T-s diagram of ideal Rankine cycle (Moran, et al., 2011)

The regeneration process involves extracting a fraction of steam flowing through the turbine from one or more positions along the turbine expansion. The heat contained by the extracted steam is used for preheating feedwater in the feedwater heaters before it is transferred to the boiler. The hot feedwater requires less energy to be converted into steam, which in turn reduces boiler fuel consumption. The extracted steam does a certain amount of work in the turbine from throttle condition to the extraction point and transfers the remaining heat to the feedwater, thus conserving the total heat, instead of losing part of the heat to the circulating cooling water in the condenser. This regeneration process improves the plant efficiency by reducing boiler heat demand and heat loss in the condenser during steam condensation.

Figure 3 shows a regeneration cycle with steam extracted at three positions from the turbine. At point 4 the turbine is fed with 1 kg superheated steam. The first steam extraction (y_a kg) is made at point 5 and is directed to Heater 1. The second extraction (y_b kg) is taken at point 6 and transferred to Heater 2. The third extraction (y_c kg) is done at point 7 and moved to Heater 3. The remaining ($1-y_a-y_b-y_c$) kg steam enters the condenser after exiting the turbine at point 8. Each unit of extracted steam transfers heat to the feedwater in the heaters and changes into condensate which is then cascaded backward and after existing Heater 3, point 18, the combined ($y_a+y_b+y_c$) kg condensate is drained to the condenser. The 1 kg condensate from the condenser is pumped through the heaters into the boiler for regeneration of steam.

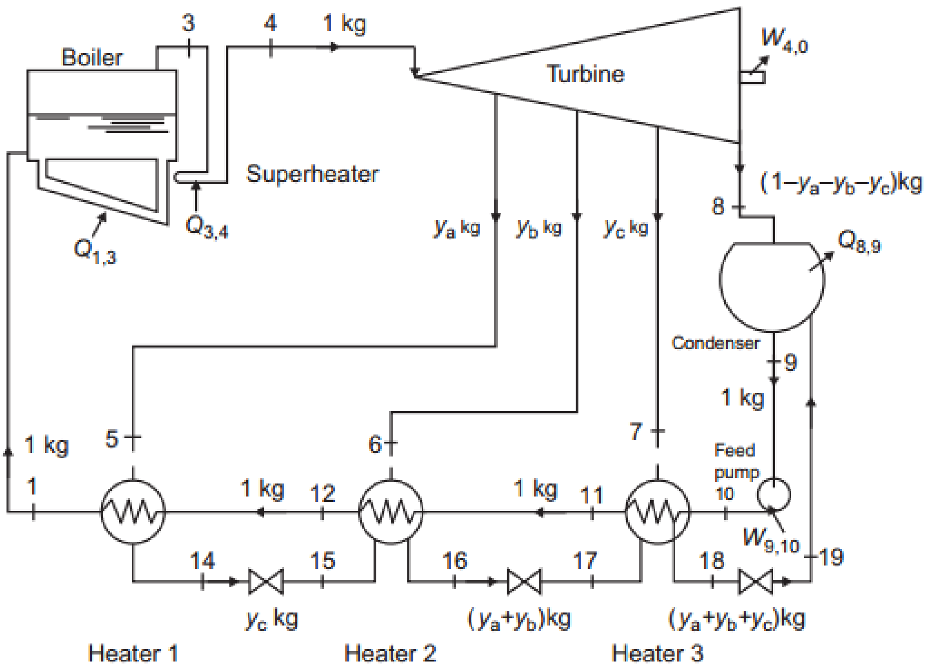


Figure 3. Triple extraction regeneration cycle (Sarkar, 2015)

Figure 4 shows the corresponding T-s diagram for the above regeneration cycle. Without the three steam extractions made at points 5, 6 and 7, the cycle would need heat addition in the boiler from point 10 to 4 to produce 1 kg superheated steam. The regeneration cycle involving steam extractions at the afore-mentioned points requires heat addition from point 1 to 4. Also only (1-y_a-y_b-y_c) kg steam losses heat in the main condenser during the condensation process, instead of 1 kg steam as would be the case if there is no steam extraction from the turbine.

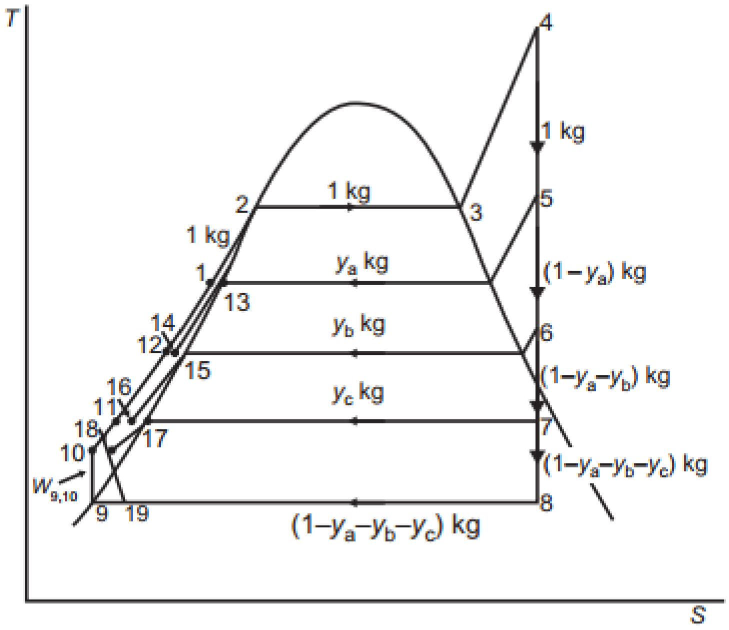


Figure 4. T-s diagram for triple extraction regeneration cycle (Sarkar, 2015)

2.2 Feedwater heating

The two key objectives of feedwater heating are: (1) to increase the temperature of feedwater, resulting in improved plant efficiency, and (2) to reduce thermal effects in the boiler by combusting less fuel for steam generation. These targets are achieved by using feedwater heaters where fractions of extracted steam from the turbine transfer heat energy to feedwater, thus increasing its temperature. The heated feedwater is converted into steam by burning less amount of fuel in the boiler.

While determining the number and type of feedwater heaters (FWHs), several factors have to be taken into account, such as the size of the plant, the operating pressure of the cycle as well as the plant economics (comparing the reduced operating costs with additional capital cost expenditure). Usually, smaller plants are equipped with fewer units, whereas, five to eight stages of FWHs are employed in the utility and large-scale industrial plants, (Woodruff & Lammers, 1977). Similarly, the choice of feedwater heater is influenced by many elements. For instance, the designer optimization method and preference, practical considerations, cost and so on. However, there are very small differences among the various types of FWHs.

The feedwater heater resulting even in a fractional efficiency increase will reduce the annual fuel costs remarkably, particularly for fossil fuelled power plants where the fuel costs represent a large portion of the total cost of electricity generation. The three types of feedwater heaters that are frequently used in steam power plants are discussed in the following paragraphs (El-Wakil, 1984).

Open or direct-contact feedwater heater - In this type of FWHs, the extracted steam and incoming sub-cooled feedwater or condensate are mixed directly to produce saturated water at the extraction steam pressure. In addition to feedwater heating, the open or direct-contact FWHs remove gases from equipment and piping systems that can cause corrosion. Therefore, such FWHs are also known as deaerating heaters (used to remove gases from feedwater). Besides the condensate pump, the open feedwater heaters require as many additional pumps as there are feedwater heaters.

Closed feedwater heaters with drains cascaded backward - The shell-and-tube heat exchangers are the most commonly used closed type FWHs. Without any mixing, the extracted steam in the shell transfers heat to the subcooled water flowing through the tubes and condenses on the shell side. The condensate is fed backward to the next lower-pressure FWH, and the lowest pressure feedwater heater may be drained into the condenser hotwell. The feedwater is pressurized only once, thus such type of FWHs do not require additional pumps. FWHs with drains cascaded backward may need a steam trap only. Steam traps are explained in section 4 of this work.

Closed feedwater heaters with drains pumped forward - These are also shell-and-tube type FWHs in which the extracted steam does not mix with the feedwater. The extracted steam condenses on the shell side by transferring heat to the feedwater flowing through the tubes. Additional pumps are required for transferring condensate to the main feedwater line.

In both types of configurations, the temperature of feedwater is increased that result in reduced boiler fuel consumption. However, one of the advantages of pumped drains over the cascaded drains is that it prevents the loss of energy that occurred when the combined cascade flows from the lowest heater (in case of drains cascaded backward) is throttled to the condenser pressure.

Figure 5 shows the two types of closed feedwater heaters. The closed feedwater heater with drains pumped forward requires a pump for transferring condensate drains to a higher-pressure line, whereas, a steam trap is used for draining condensate to the lower-pressure heater or condenser in closed feedwater heater with drains cascaded backward.

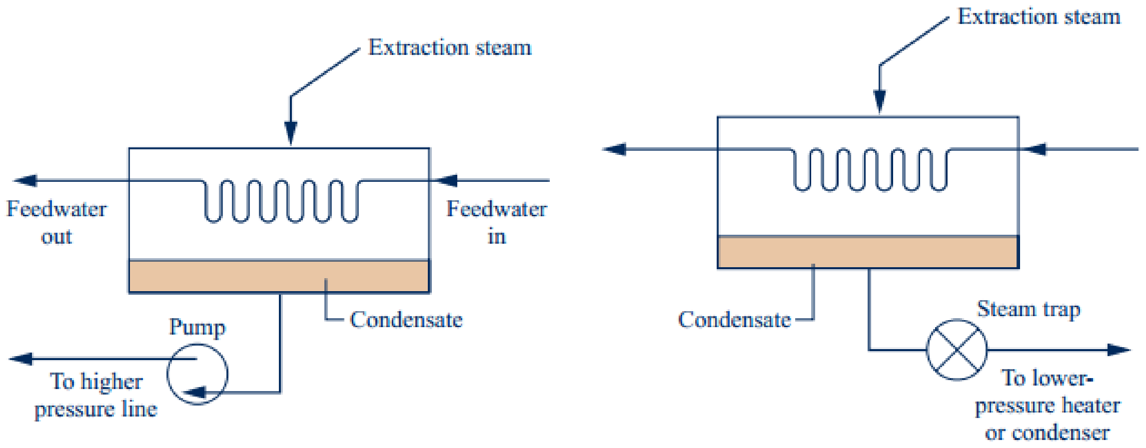


Figure 5. Closed FWH with drains pumped forward (left), and drains cascaded backward (right) (Moran, et al., 2011)

The performance of closed feedwater heaters is deteriorated by the accumulation of non-condensable gases in the shell, flooding of the shell with condensate or deposits on the tubes. The non-condensable gases are vented to the atmosphere when the heater is operating with a positive pressure in the shell, however, in situations where the pressure in the shell is below the atmospheric pressure, the gases are vented to a condenser, steam jet or any other vacuum-producing auxiliary. The condensate is drained through steam traps to a vessel having pressure significantly lower than that of the shell but if the low-pressure vessel is not available a condensate pump is required for discharging condensate from closed feedwater heaters. Hard water is the main source of deposits on the tubes of closed feedwater heaters that restrict the flow and slow down the heat transfer rate. (Woodruff & Lammers, 1977)

3 STEAM CONDENSATE SYSTEM

The condensate systems of steam power plants vary according to the design of the plant. Before discussing the layout of a typical condensate system, it is necessary to understand what actually condensate is, where condensate generates in steam power plants, why condensate should be recovered and how condensate responds to pressure reduction in a system. All these points are covered in this section.

3.1 What is condensate and where it forms

Figure 6 depicts the latent heat and sensible heat required for changing the state of water at atmospheric pressure. Latent heat is associated with the change in state at constant temperature and pressure. For example, ice at 0°C turns into ice water by absorbing latent heat of 334 kJ/kg at the same temperature. Similarly, at 100°C boiling water will change into dry steam when provided with a latent heat of 2257 kJ/kg. Sensible heat of a solid, liquid or gas is associated with temperature changes. The figure shows that for transforming ice water at 0°C into boiling water of 100°C, sensible heat of 418 kJ/kg must be added.

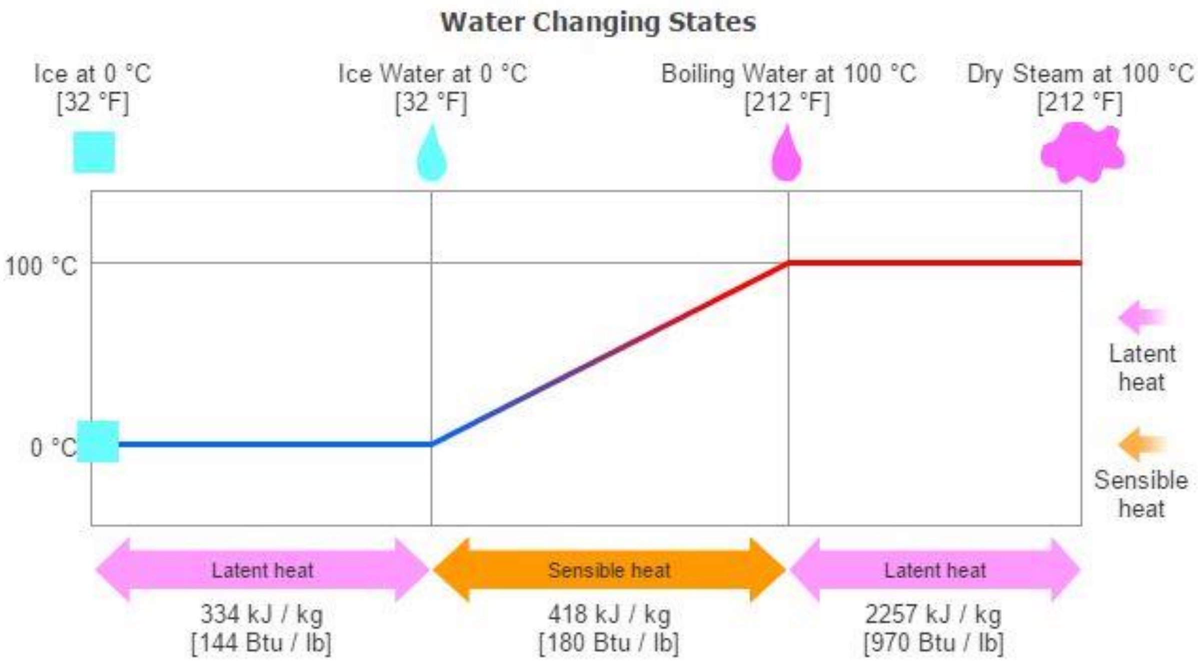


Figure 6. Latent heat and sensible heat of water (TLV, 2017)

The same amount of latent heat and sensible heat should be released for the reverse process to happen. For instance, in the above figure dry steam at 100°C should give up latent heat of 2257 kJ/kg to change into boiling water having the same temperature and pressure (atmospheric pressure). Thus by absorbing latent heat (enthalpy of evaporation) water changes into steam and by releasing this heat steam changes back into the high-temperature water, which is commonly known as condensate. The hot condensate formed is saturated water containing sensible heat because during phase transition the temperature does not change. This process of transformation of steam into water (condensate) by releasing enthalpy of evaporation is called condensation.

In steam power plants, the condensation process can be observed at the main condenser as well as feedwater heaters where steam condenses into liquid (condensate). Also, a small amount of condensate may appear in steam pipelines due to radiation heat loss. The process of condensation occurs at constant pressure and temperature. The latent heat released is utilized to heat up the incoming liquid, process or equipment, depending on the desired requirement. The resulting condensate is pure water having the same temperature and pressure as steam and thus should be recovered and transported to the boiler for regeneration of steam. The recovery of hot condensate plays a vital role in the overall efficiency of the plant as discussed in the following paragraphs.

3.2 Benefits of condensate recovery

The purpose of condensate recovery is to reuse the condensate (hot water containing sensible heat) instead of throwing it away. As condensate is treated water and contains heat, recovering it will result in significant savings in terms of energy, chemical treatment as well as makeup water. The condensate can be effectively utilized in a number of ways, for instance (TLV, 2017):

- In the form of hot water for cleaning purposes
- In the form of heating agent in certain heating systems
- In the form of flash steam for reusing
- In the form of heated feedwater for the boiler

Hot condensate recovery not only results in saving energy and water resources but also enhances working conditions and cuts the plant's carbon footprint. Some of the advantages of condensate recovery are presented below.

Lower fuel costs

Condensate contains sensible heat that accounts for approximately 10% to 30% of the total heat contained in the live steam. Supplying hot condensate to the boiler will require less heat for steam production, thus the boiler efficiency will increase as the input fuel consumption decreases. The boiler fuel needs can be potentially reduced from 10% to 20% by economically recovering hot condensate.

Reduced water costs

Water requires proper treatment and preparation before it is used in the boiler. The condensate free of impurities can be directly transferred to the boiler without any additional treatment. Therefore, using condensate, which is already treated water, the costs of water treatment and preparation are avoided.

Safety and environmental benefits

As stated earlier, the boiler fuel consumption decreases when hot condensate is fed into the boiler. Lower boiler fuel consumption means lower CO_2, NO_x and SO_x emissions and thus reduced air pollution. Discharging condensate directly to the atmosphere generates noise and vapour clouds. Power plants having proper condensate recovery system constraints vapour clouds, decreases noise and hampers water accumulation on the ground, and consequently improves the working environment. Furthermore, condensate having no impurities reduces the need for boiler blowdown and corrosion in the pipelines.

3.3 Effect of pressure reduction on condensate

The condensate in a system is greatly influenced by pressure variations. When condensate flows from higher pressure to lower pressure, part of it changes into flash steam (see section 5 for details). Even though the amount of flash steam generated may be small, the resulting mixture of condensate and flash steam has a high specific volume that leads to huge velocities in the piping network and hence difficult to handle.

For example, consider condensate (saturated water) at 2.3 bar is discharged to a line operating at atmospheric pressure. The various properties are noted down from steam tables.

At 2.3 bar,

Saturated temperature = 125°C

Saturated liquid enthalpy = 524 kJ/kg

Saturated liquid specific volume = 1.1 l/kg

At atmospheric pressure, 1 bar,

Saturated temperature = 100°C

Saturated liquid enthalpy = 417 kJ/kg

Saturated liquid volume = 1.0 l/kg

Suppose on the downstream side, at atmospheric pressure, 5% of the saturated water (condensate) changes into flash steam. The saturated vapour enthalpy and volume obtained from the steam tables are:

Saturated vapour enthalpy = 2675 kJ/kg

Saturated vapour volume = 1694 l/kg

The corresponding specific volume of the mixture consisting of 5% flash steam and 95% condensate will be:

Specific volume of mixture = $(1 \times 0.95) \times (1694 \times 0.95) = 86$ l/kg

This pressure reduction in a system (pipeline) will cause condensate to change back into steam (flash steam). The steam generated may be small but the volume of the resulting mixture is extremely large. As shown in the above example, the saturated liquid volume of the condensate at 2.3 bar was 1 litre, but when this condensate is discharged to atmospheric pressure with only 5% of it changed into steam, the volume of the mixture is 86 litres. This increase in flow volume is not easy to handle and causes the problem of leakage, therefore, it is imperative to understand the nature of condensate in a system (condensate pipelines) in advance to its design.

3.4 Condensate system of steam power plants

The condensate system of steam power plants is associated with the feedwater heating system. The condensed steam or feedwater from the condenser hotwell is passed through a number of heat exchangers, called feedwater heaters (FWHs), where its temperature is increased by absorbing heat from the steam extracted from the turbine at different positions. This process is known as regeneration and improves the efficiency of steam power plants by decreasing the boiler fuel consumption. The fractions of extracted steam after transferring heat energy (enthalpy of evaporation) to the feedwater in FWHs changes into condensate. The condensate formed is then cascaded backward to lower pressure FWHs in the network or pumped forward to higher pressure FWHs or deaerator, depending on the design of condensate system. Thus the proper operation of both condensate and feedwater heating systems is crucial for the better performance of steam power plants.

The processes of handling the condensate (resulting from extracted steam as well as condensation in steam pipelines) and feedwater heating and transferring it to the boiler require a complex arrangement of heat exchangers and pumps, with hundreds of valves interconnected by several kilometres of pipework. These different networks of pipes, valves and heat exchangers result in many possible flow paths. The determination of appropriate flow paths and elimination of undesirable routes is extremely important for the design of a successful system (feedwater and condensate system).

Figure 7 shows a typical configuration of condensate and feedwater heating system of a steam power plant. Before analysing the various flow paths in detail, it is important to keep in mind that the blue solid lines in the figure represent the condensed steam that is formed when steam from the last turbine is condensed in the condenser. These lines also represent feedwater. The blue dashed lines show the condensate drains from FWHs and are basically representing the condensate that is generated when fractions of extracted steam from the turbine transfer enthalpy of evaporation to feedwater in the FWHs.

The feedwater heaters in this system are of the surface type. The condensed steam/feedwater (solid blue line) from the condenser hotwell is pumped by the condenser extraction pumps through the gland steam condenser and low-pressure (LP) heaters (LP1, LP2, LP3) to the elevated deaerator. The high-level position of the deaerator provides the net positive suction head (NPSH) required by the boiler feed pumps. The NPSH has been explained in the following section. The feedwater from the deaerator is then pumped by the turbine driven boiler feed pump through the feedwater flow regulating valves and the high-pressure (HP) heaters (HP5A, HP5A, HP6A, HP6B) to the boiler.

While passing through the LP and HP heaters, the temperature of the condensed steam or feedwater is increased by steam extracted at different pressures (LP, IP, HP) from the turbine. Steam from LP sections of the turbine (green thin solid lines) is directed towards the LP heaters (LP1, LP2, LP3) that heat up the incoming condensed steam/feedwater. The extracted steam changes into condensate by giving up its enthalpy of evaporation to the feedwater. The condensate drains (blue dashed lines) from these LP heaters is collected in the condenser flash vessel (CFV) and is then finally discharged into the condenser hotwell. The importance of the flash vessel in condensate systems has been explained in section 6.

Similarly, in the HP heaters (HP5A, HP5B, HP6A, HP6B) the temperature of condensed steam or feedwater is further increased by steam extracted from IP and HP sections of the turbine. As shown in figure, steam from IP section of turbine (green thick dashed lines) is used for heating feedwater in the lower HP heaters (HP5A, HP5B), whereas, steam taken from HP section of turbine (red dashed lines) is used for heating feedwater in the upper HP heaters (HP6A, HP6B). The condensate drains from these heaters (blue dashed lines) is transferred to the condenser.

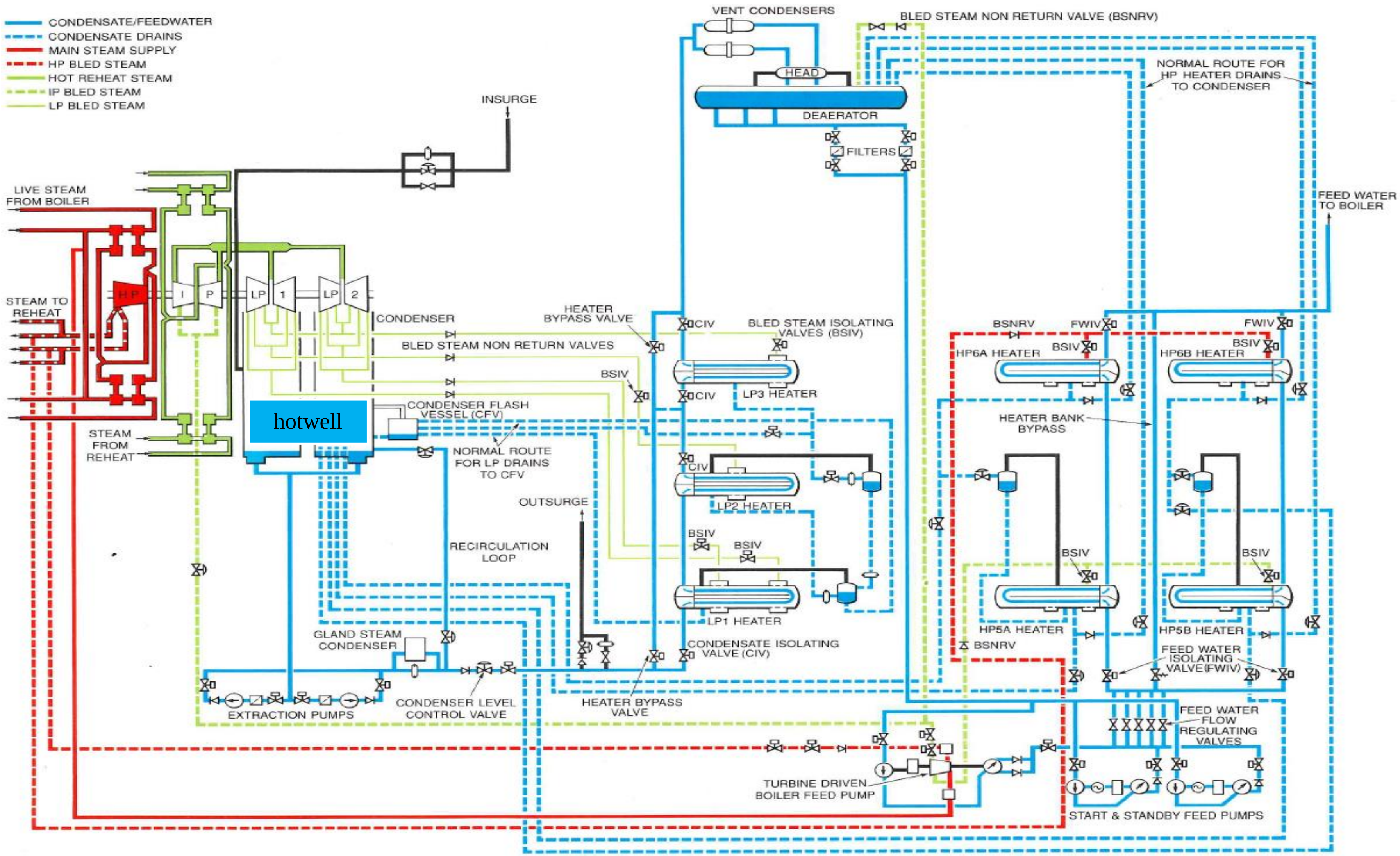


Figure 7. Condensate and feedwater heating system of a steam power plant (Central Electricity Generating Board, 1971)

4 MAJOR COMPONENTS OF CONDENSATE SYSTEMS

Condensate systems of steam power plants consist of a great number of components and it is difficult to cover them all in this work. Here some of the main components and systems dealing with condensate flow are presented.

4.1 Steam traps

The condensate formed in steam pipelines or steam using equipment should be removed quickly as its accumulation adversely affects the system performance. This is done with the help of steam traps which are basically automatic valves that allow condensate (also non-condensable gases, such as air and CO_2) to discharge from the system while keeping the live steam. These steam traps are capable to differentiate between the live steam and the condensate in many different ways and are broadly divided into three main groups, namely mechanical, thermostatic and thermodynamic steam traps.

Mechanical steam traps (operate by changes in fluid density) - The operation of mechanical steam traps is based on density variation between condensate and steam. Ball float traps and Inverted bucket traps are the two main types of mechanical steam traps, (Spiraxsarco, 2005). The working principle of an inverted bucket steam trap is illustrated in Figure 8. At the beginning, the bucket is down and the valve is opened. The incoming condensate flows under the bucket, fills the body of the trap, fully submerges the bucket and thus causing condensate to drain. Steam also flows the same way, enters under the bottom of the bucket. However, steam accumulates at the top, transmitting buoyancy that causes the bucket to move towards its seat until the valve closes completely. The air and CO_2 also pass through the bucket vent and collect at the top of the trap.

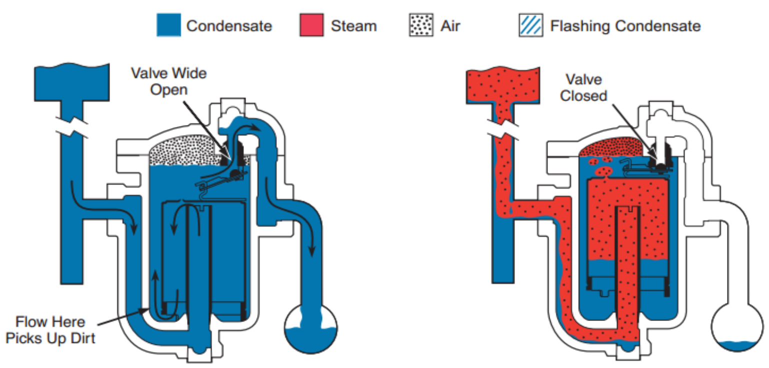


Figure 8. Working principle of an inverted bucket steam trap (Armstrong, 2011)

Thermostatic steam traps (operate by changes in fluid temperature) – The three major mechanisms for thermostatic steam traps operation are based on metallic expansion, liquid expansion, and vapour pressure, (Goodall, 1981). Figure 9 shows the working principle of a thermostatic trap based on vapour pressure. When condensate and air enter the trap, the thermostatic bellows element contracts, thus opening the valve. When steam flows into the trap, the increase in temperature causes the charged bellows element to heat up, which in turn increases the vapour pressure. When the pressure inside the element and the pressure in the trap body become balanced, the element expands by the spring effect of the bellows, causing the valve to close. As the temperature in the trap drops below the saturated steam temperature, the bellows are contracted by the imbalanced pressures and the valve opens.

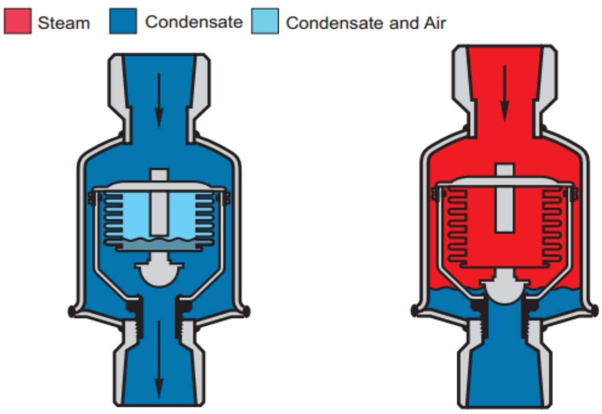


Figure 9. Working principle of a thermostatic steam trap (Armstrong, 2011)

Thermodynamic steam traps (operate by changes in fluid dynamics) - These traps operate in situations when condensate changes into flash steam (discussed in section 5). Thermodynamic, disc, impulse and labyrinth are some of the common types of thermodynamic steam traps, (Spiraxsarco, 2005). Figure 10 shows the working principle of a disc type thermodynamic steam trap; (i) the disc moves upward by the incoming pressure of the condensate, the cool condensate and air move under the disc and discharge from the trap, (ii) the hot condensate when enters the chamber experiences a pressure reduction and some amount of it turns into flash steam that while moving with greater velocity creates a low pressure area under the disc and thus the disc moves downward to the seat, (iii) the pressure exerted by the flash steam on the disc closes the trap, (iv) when the flash steam condenses, the trapped pressure in the upper chamber decreases causing the disc to move upward and thus the trap opens.

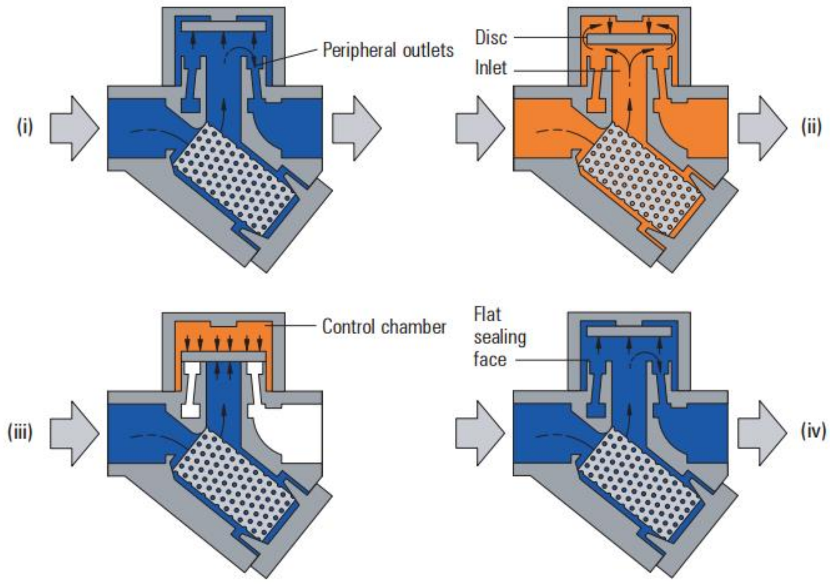


Figure 10. Working principle of a thermodynamic steam trap (Spiraxsarco, 2005)

Characteristics of a good steam trap

Different applications require different types of traps and all have their advantages and disadvantages. The steam trap selection is therefore dependent on several factors. Some of the important features of a good steam trap are: (Armstrong, 2011)

- **Minimum steam loss:** a good steam trap opens only for condensate and non-condensable gases while offering lowest flow or leakage of live steam
- **Long life and reliable:** works properly, lower maintenance and serves for longer time
- **Resistive to corrosion:** withstand corrosion caused by acidic/oxygen-laden condensate
- **Air and CO_2 venting:** it should be able to remove air from the system that deteriorates the heat transfer process. The trap should be operable at or near steam temperature and vent CO_2 at this temperature. Because the solubility of CO_2 in condensate is lower at higher temperatures and thus the formation of carbonic acid is avoided
- **Capable to operate at actual back-pressure:** in situations where the return lines are pressurised by any means, the stem trap should not be effected by such variations
- **Operates efficiently in presence of dirt:** the condensate loop contains dirt, even small debris pass through the strainers or separators and enter the steam lines, thus a good steam trap should work properly even when the system contains some amount of dirt

4.2 Flash vessels

Flash vessels are used to separate flash steam from condensate. As discussed in section 3 (effect of pressure reduction on condensate), condensate changes into flash steam due to pressure differences in the pipelines. The coexistence of condensate and flash steam causes water hammer in the condensate piping network, and thus are separated with the help of flash vessels. A detail description of the flash vessel is presented in section 6.

4.3 Pumps

Due to their substantial number of types and applications, pumps have been classified on several bases. For instance, pumps that are used in power plants can be broadly divided into dynamic pumps (such as centrifugal pumps) and displacement pumps (such as reciprocating and rotary-type pumps). Also, pumps are generally divided into four main categories as reciprocating pumps, rotary pumps, centrifugal pumps and other special pumps (hydraulic-ram pumps, jet pumps, gas-lift pumps, etc.). Thus the subject of pumps is quite broad. In this section, some of the important aspects of pumps used in condensate systems are presented.

The basic steam power plant cycle incorporates a combination of feedwater heating and condensing cycle and hence requires at least three pumps.

- Condensate pump that is used to transfer condensate to the deaerator from the condenser hotwell
- Boiler feed pump that is used to transfer feedwater from the feedwater heaters either to the economizer or to the boiler steam drum
- Circulating water pump that is used to circulate cooling water through the main condenser in order to condense the steam exiting the turbine

The condensate pump transfers condensate or feedwater from the condenser hotwell to the boiler feed pump while maintaining a continuous feedwater supply through the feedwater heaters. The head required for the operation of the pump is based on the type of installation.

A positive differential pressure from the condensate source to the destination (feedwater heater, deaerator, main condenser) is always required when the recovered condensate is to be reused. In very few circumstances, the trap’s inlet steam pressure is enough to overcome the system back pressure and there is no need to use additional pumps. However, the majority of the condensate systems have negative differential pressure and need extra pumps for transferring condensate to the desired location. In such situations, it is important to know about the suction conditions of the pump which greatly affect the operation of centrifugal or rotary pumps. The suction performance of a pump (the relation between the capacity and suction conditions) involves a quantity known as NPSH.

The Net Positive Suction Head (NPSH) is the energy contained in the liquid at the pump datum. The required NPSH is different from the available NPSH. The former is the energy required to fill a pump on the suction side and control friction and flow losses from the suction connection to that point in the pump where more energy is added. It is a characteristic of the pump and varies with the design, size and operating conditions of the pump, and is provided by the manufacturer. The available NPSH is the energy within the liquid at the suction connection of the pump and is greater than the energy of the liquid due to its vapour pressure. It is a characteristic of the system.

As the NPSH depends on the design of the pump, it is important to maintain proper NPSH at the pump. In conditions when the static pressure at the impeller vanes gets lower than the vapour pressure corresponding to its temperature, a certain amount of water changes into steam, resulting in cavitation. Cavitation causes erosion damages to the impeller of the pump when operated for longer periods. (Woodruff & Lammers, 1977)

4.4 Valves

The valves used for automatic control of steam, condensate and other industrial fluids have basically two types of spindle movement, namely linear movement, and rotary movement. Globe valves and slide valves are the types of valves having linear spindle movement, and ball valves, plug valves, butterfly valves and their variants show rotary spindle movement.

According to the European standard EN 736-1:1995, the control, regulating and isolating valves are defined as under:

- **Control valves** are used to change fluid flow rate in the process control system
- **Regulating valves** are used in many different positions between fully-opened and fully-closed

- **Isolating valves** are used either in the fully-opened or fully-closed position

Ball valve

As shown in Figure 11, these valves consist of a ball that opens and closes the valve. The valve opens when the ball hole aligns with the pipe ends. The rotation of the ball causes the valve to close and shut completely when it is perpendicular to the pipe ends. These valves are preferred in cases of remote isolation and control requirements. The flow characteristics of such valves are varied by changing the shape of the ball hole. These valves can be used in flow conditions up to 100°C.

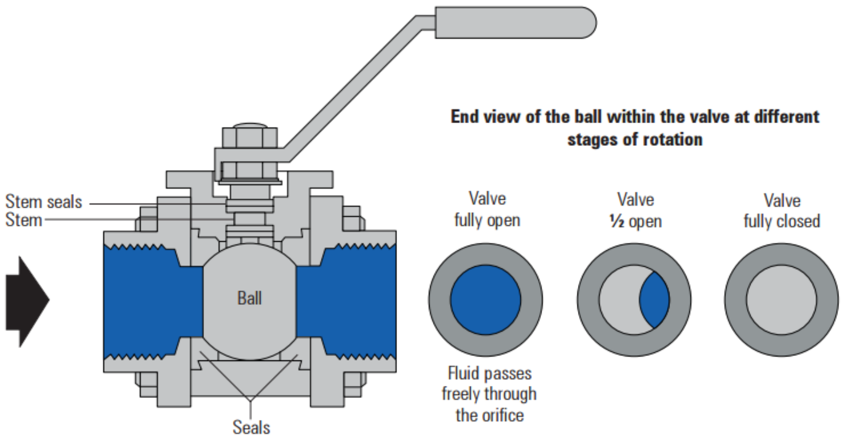


Figure 11. Ball valve in fully-opened position (Spiraxsarco, 2005)

Butterfly valves

These valves consist of a disc. When the disc gets parallel to the pipe wall, the valve opens completely. As the disc rotates and becomes perpendicular to the pipe wall, the valve closes fully. The fluid flowing through these valves experiences small resistance, thus resulting in pressure losses. Butterfly valves are compact, light, less expensive and cause lower head loss, Figure 12. (Central Electricity Generating Board, 1971)

Needle valves

These valves are used to control relatively small flow rates. The construction of needle valves is similar to that of globe valves. These valves consist of a long needle that serves like a disc. The movement of the needle through the orifice controls the flow rate very finely, Figure 12. Needle valves are frequently used as component parts of other more complex valves, such as reducing valves.

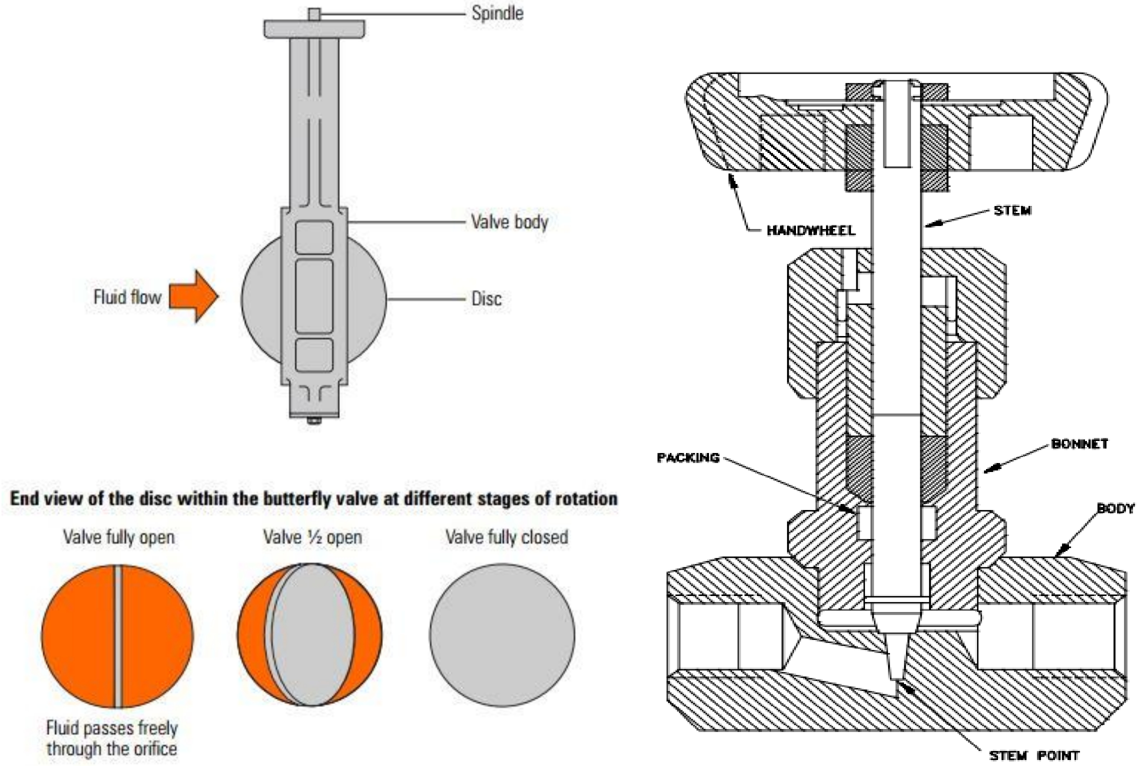


Figure 12. Butterfly valve and the needle valve (Spiraxsarco, 2005)

4.5 Strainers

Strainers are used to arrest small pieces of debris, such as rust, weld metals, jointing compounds and other solid particles, from the steam and condensate systems. Such small particles malfunction valves and components, resulting in more downtime and increased maintenance. It is recommended to use strainers upstream of every control valve, flow meter, and steam trap. Figure 13 shows cut section of a strainer. Steam or water enters through inlet A, crosses the perforated screen B and exits through the outlet C. The steam and condensate can easily pass through the screen but dirt cannot. The cap D is removed to clean the screen.

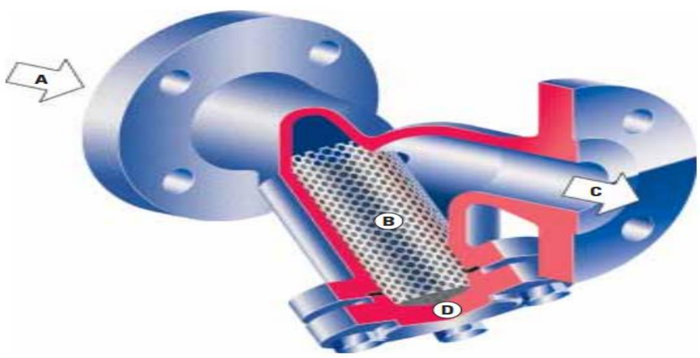


Figure 13. Cut section of a strainer (Spiraxsarco, 2005)

4.6 Steam drain system

Before starting a steam turbine it is necessary to warm-up the pipelines of live steam, cold reheat steam, and hot reheat steam as well as the turbine control and stops valve bodies. This process is performed by a steam drain system that circulates hot steam through various pipelines and valve bodies. The stream drain system also avoids water accumulation in the pipelines during the start-up and any operating condition. The accumulation of water in steam pipelines causes water or wet steam to enter the hot turbine, resulting in severe damages. The steam drain systems are provided with drain pots that carry condensate from the cold pipelines to the condenser, thus preventing water accumulation in the pipelines.

Figure 14 shows a typical configuration of steam drain system for a motive steam pipe. Motive steam pipe supplies live steam to the turbine for the production of power or to an auxiliary turbine, such as turbine driven boiler feed pump.

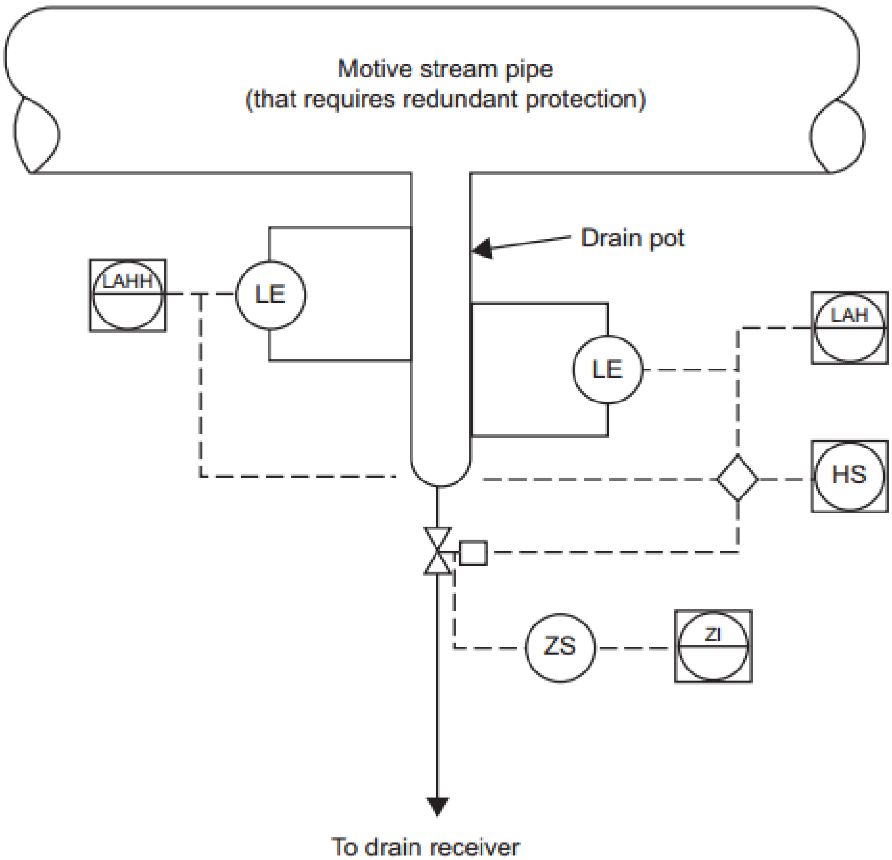


Figure 14. Typical configuration of steam drain system for a motive steam pipe (Sarkar, 2015)

4.7 Extraction steam system

The overall efficiency of steam power plants has been improved by preheating feedwater and condensate before transferring to the steam generator. The steam extracted from the turbine is used for preheating both feedwater and condensate in the feedwater heaters and deaerator heater. This process is commonly known as regenerative heating.

The extraction steam system shown in Figure 15 consists of a high-pressure (HP) section and a low-pressure (LP) section. In the HP section, the feedwater is preheated by the steam extracted from the cold reheat line and IP turbine (also HP turbine in case of large steam turbines of 800 MW or higher). In the LP section, the condensate is preheated by the steam extracted from IP turbine exhaust and LP turbine. The extraction steam system is also equipped with a number of valves for proper operation. (Sarkar, 2015)

4.8 Heater drains and vents systems

The accumulation of condensate (resulting from extracted steam) in closed feedwater heaters is highly prevented because of its negative consequences, such as lower heat transfer rate. In normal conditions, the condensate from each feedwater heater is drained to the lower-pressure heater in the cascade. However, in situations when HP heater is not available, the condensate from HP heater is transferred to the deaerator and the LP heater condensate is drained to the condenser. Also from each heater, an alternate drain to the condenser is provided, as shown in Figure 15. Heater drains are mostly gravity type.

The purpose of a heater vent system is to remove non-condensable gases from the feedwater heaters and the deaerating heater. As shown in Figure 15, the heaters have two vent lines, a staring vent line, and a normal vent line. The starting vent line remains closed during the normal operation. This line ends with an isolation valve which is opened and releases trapped gases to the atmosphere before the vent line starts to operate. The normal vent line always remains open when the heater is in use. This line is connected with the condenser shell and contains an orifice that controls the flow. (Sarkar, 2015)

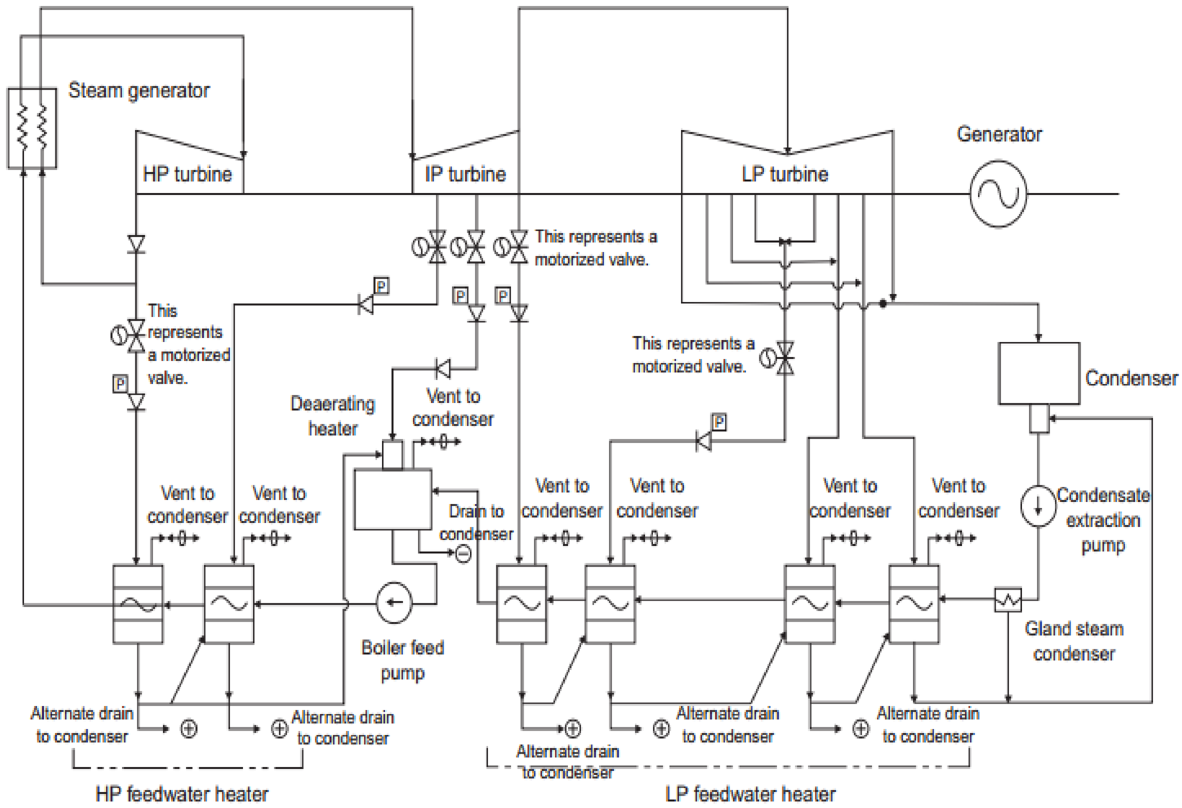


Figure 15. Extraction steam, heat drains and vents system (Sarkar, 2015)

4.9 Condensate dump systems

The condensate from the condenser hotwell is pumped to the deaerator by the condensate extraction pumps. The hotwell is equipped with a recirculation line from the outlet of gland steam condenser in order to protect the running pumps in the events when condensate flow to the deaerator heater decreases by a certain minimum limit.

The condensate dump system is basically used for maintaining a proper level of hotwell. The condensate from the condensate storage tank is transferred to the hotwell when its level falls down below a certain level. Also, makeup water is added to the condenser when the hotwell level cannot be maintained by the condensate storage tank. When the level in the hotwell exceeds its storage capacity or a certain limit, the condensate is dumped back into the condensate storage tank.

For the minimum hotwell storage capacity the Heat Exchanger Institute (HEI) recommends, "....volume sufficient to contain all of the condensate produced in the condenser in a period of 60 s under conditions of design steam load." However, sizing of the condenser hotwell may vary according to the industrial practices. Figure 16 shows a typical configuration of a condensate dump system.

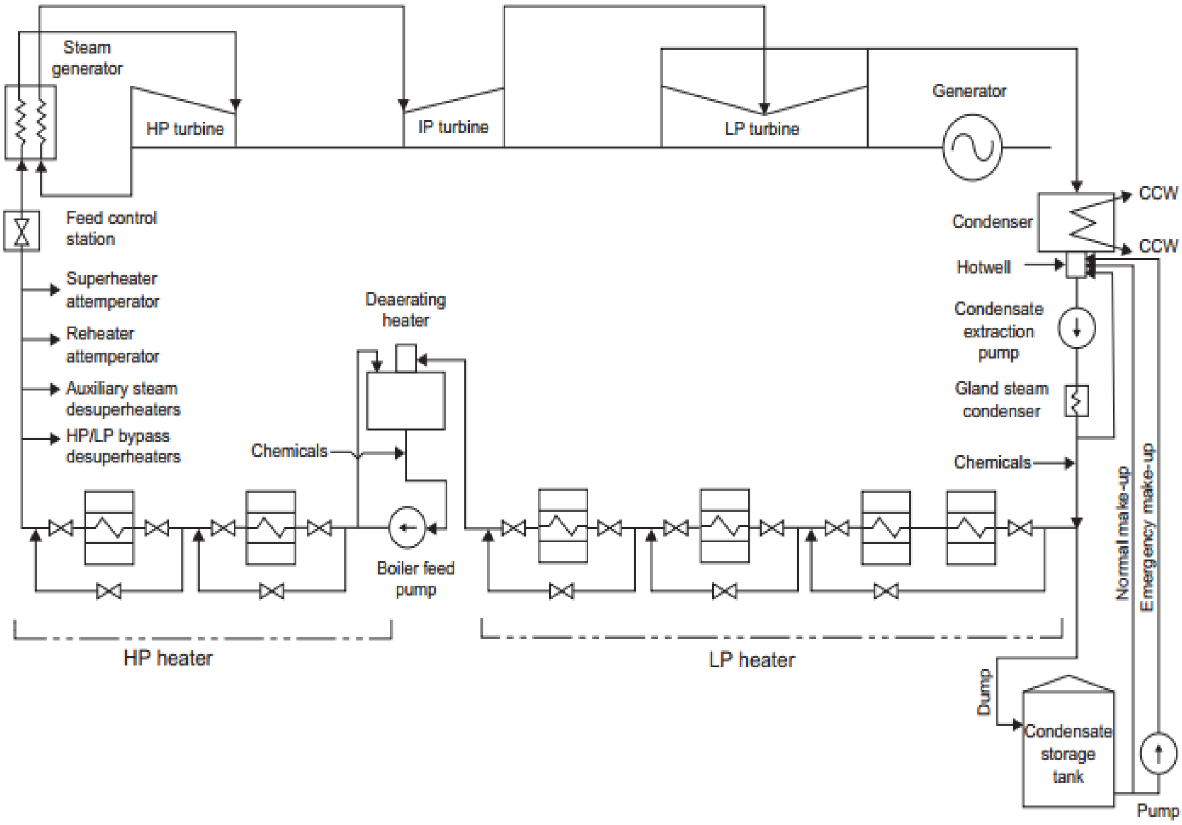


Figure 16. Condensate dump system (Sarkar, 2015)

5 PROBLEMS WITH CONDENSATE

Steam power plant engineers usually concentrate on steam supply and the heat it provides to feedwater for improving plant efficiency and reliability by addressing various problems, such as piping leaks, steam trap leaks, and insulation. They overlook the importance of steam condensate system unless significant issues already exist, such as water hammer, high back pressure, and pipe damages. Hence, to achieve higher productivity, energy efficiency, and site reliability, the design of steam condensate system should be given equal attention.

While flowing through the pipes and pumps, condensate results in several problems that adversely affect the performance of the system. Also, the presence of air and other non-condensable gases deteriorate different processes. This section deals with some of the most common problems associated with steam condensate system.

5.1 Flash steam

Flash steam is different from live steam in a sense that the former is not produced in the boiler. It originates in situations where condensate at higher-pressure flows towards the lower-pressure side, provided the condensate temperature on the higher-pressure side is greater than the saturation temperature on the lower-pressure side. This phenomenon is mostly occurring in steam traps that are used to remove condensate from steam lines. Consider the situation shown in Figure 17. On the higher-pressure side of the steam trap, condensate at 5 bar-g (gauge pressure) and saturation temperature of 159°C containing heat energy of 671 kJ/kg are allowed to flow to the lower-pressure side of 0 bar-g and saturation temperature 100°C. From the first law of thermodynamics, the heat energy should be balanced on both sides in order to satisfy the principle of energy conservation. But at 0 bar-g and 100°C saturation temperature the condensate heat energy should be 417 kJ/kg. The (671 - 417) 254 kJ/kg excess energy will change some of the condensates into flash steam.

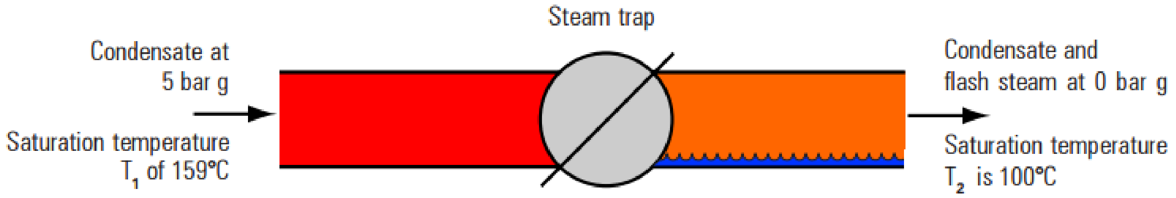


Figure 17. Condensate changes into flash steam due to pressure reduction (Spiraxsarco, 2005)

There are many factors that affect the formation of flash steam, the most important among these is the pressure drop. The smaller the pressure difference across the inlet and outlet of a steam trap the lower is the flash steam generation. Figure 18 shows an experimental setup made by (TLV, 2017). During the experiment, it was observed that great amount of flash steam generated when condensate at 10 bar-g (1.0 MPaG) was discharged to 0 bar-g (0 MPaG), however, less flash steam was formed when the same amount of condensate is discharged to a 3 bar-g (0.3 MPaG) closed system.

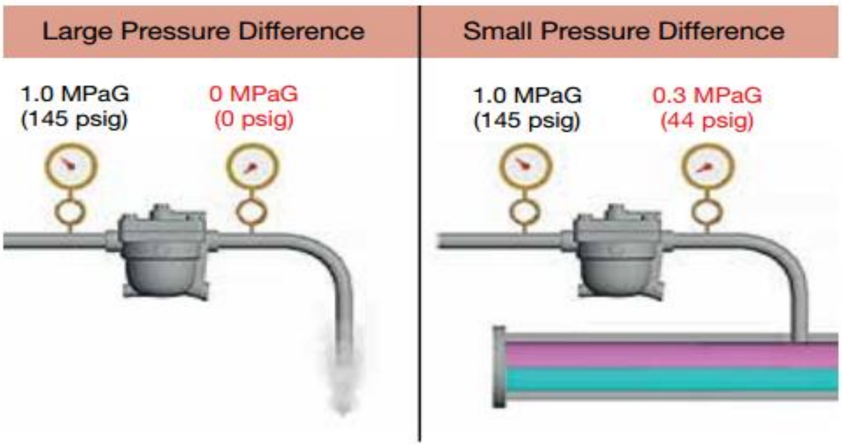


Figure 18. Pressure difference and generation of flash steam (TLV, 2017)

The presence of flash steam in condensate system is problematic. The volume of flash steam (vapour) is many times the volume it has as condensate (liquid). For instance, condensate at 10 bar will have about 1500 times the volume when it flashes to steam at atmospheric pressure (1 bar). This huge expansion in volume will pressurize the condensate piping systems that had not been properly designed to accept the volume of flash steam. Thus the proper drainage of steam heating equipment, such as feedwater heaters, and performance of some types of steam traps are impaired. Also vapour clouds are formed when flash steam is released to the open atmosphere, thus negatively affecting the working environment.

For proper sizing of condensate return lines that are sufficient to accommodate two-phase flow (condensate + flash steam) the amount of flash steam generation should be accurately determined. The following equation can be used to calculate the flash steam produced at the lower-pressure side. (TLV, 2017)

$$Flash\ \% = \frac{(h_f\ at\ P_1) - (h_f\ at\ P_2)}{h_{fg}\ at\ P_2} \times 100 \qquad (1)$$

Where,

P_1 is the higher-pressure (bar)

P_2 is the lower-pressure (bar)

h_f is the liquid enthalpy (kJ/kg)

h_{fg} is the enthalpy/heat of evaporation (kJ/kg)

Flash steam is of the same quality as the live steam and thus should be recaptured for reuse. Recovering flash steam, similar to condensate, helps in the better working environment (by avoiding vapour clouds) and energy savings. (Spiraxsarco, 2005)

5.2 Water hammer

Condensate film forms on the walls of steam pipes when steam loses heat energy. The thickness of the film increases as it flows through the pipe and turns into an incompressible water slug having high density. Figure 19 illustrates the formation of water slug in a steam pipe. As the condensate film gravitates through the pipe, its thickness increases and finally fills the cross-sectional area of the pipe.

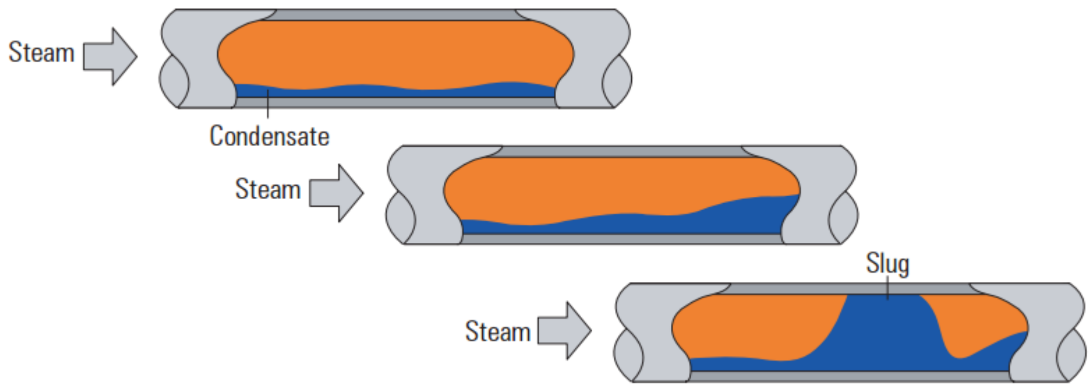


Figure 19. Solid slug of liquid condensate in steam supply system (Spiraxsarco, 2005)

This slug of liquid condensate while traveling with the steam (steam velocity 25 – 30 m/s), possesses high kinetic energy and any obstruction in its path, such as bend or tee in the pipework, changes the kinetic energy into pressure energy and thus a pressure shock is experienced by the obstruction. The collision of high-speed condensate slugs with obstructions (pipework fittings, valves, etc.) causes noise and vibration in the system and is called water hammer. This type of hammering is known as condensate-induced water hammer as it is the condensate that produced it, as shown in the upper drawing of Figure 20.

On the other hand, in the condensate return lines, water hammer is caused by steam and is known as steam-induced water hammer. This type of hammering occurs due to the presence or leakage of small amounts of flash steam or live steam in the condensate return pipelines. Figures 20 (lower drawing) shows condensate line with the small amount of steam in the form of a pocket. The steam mass may be small but its volume is large and since the mass of the steam pocket is much smaller compared to the condensate mass, the heat transfers rapidly from the steam to the condensate causing the steam pocket to collapse, thus producing an exceptionally low-pressure void which is quickly filled by the condensate. The condensate while rushing to fill the void strikes with the pipe wall generating shock waves and hammering sound.

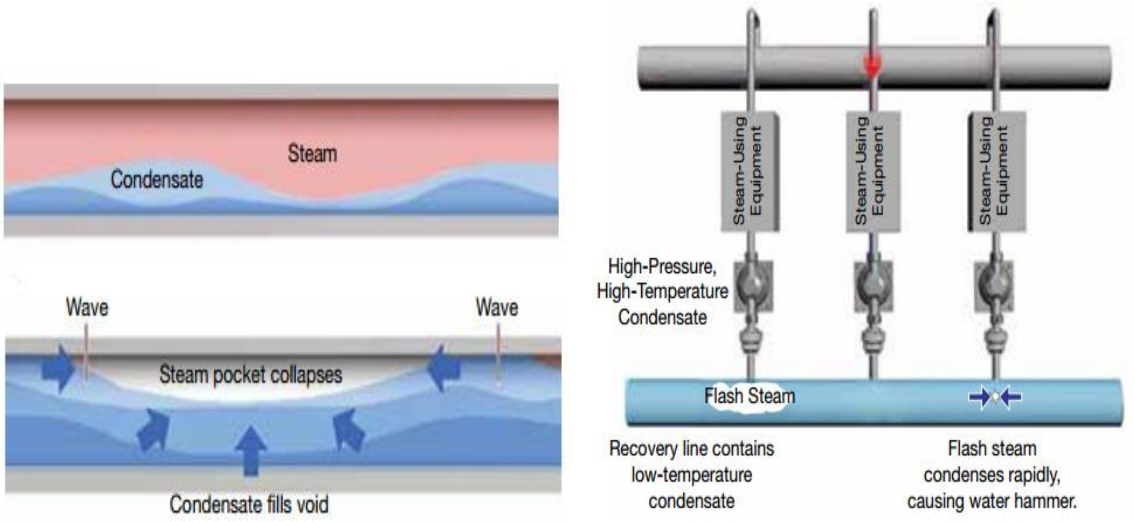


Figure 20. Steam-induced water hammer (Risko, 2016)

Water hammer is caused by several other factors. Figure 21 shows three sources of water hammer. The use of concentric reducer causes a small amount of condensate to accumulate at lower points of larger diameter pipes, thus leading to water hammer. Similarly, condensate accumulation at the bottom of rising steam lines (riser) causes water hammer. Also, strainers with hanging basket restrict steam and condensate flow, resulting in water hammer. Bending of pipelines due to poor support or support failure can be another reason for water hammer to happen. Furthermore, insufficient drainage of steam pipelines and wrong operation of valves are among the most common factors that produce water hammer.

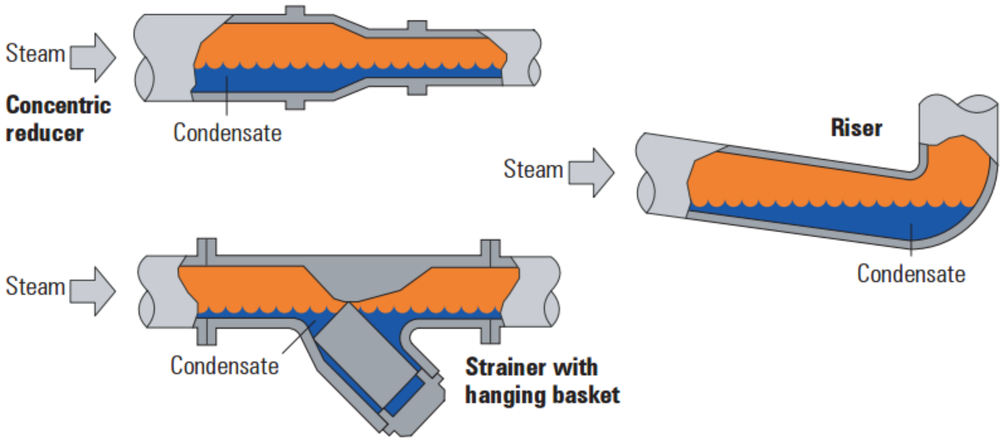


Figure 21. Potential sources of water hammer (Spiraxsarco, 2005)

Water hammer can be noticed by the noise and movement of pipes that it produces. In severe conditions, water hammer will break pipeline equipment. Reduced life of pipework equipment, fractures in piping fittings and loss of live steam are some of the serious problems caused by water hammer.

5.3 Air and non-condensable gases

Despite the fact that various steam traps and other equipment are used to take air and non-condensable gases out of the system, there are always chances that these gases enter the condensate network. During the plant start-up, air is present in the equipment and steam supply pipelines. Also when the plant is shut down and the steam condenses, air flows inside due to vacuum. Boiler feedwater can be another source of air entering the system. Additionally, air enters through equipment and due to pipe leakages. Furthermore, carbon dioxide, nitrogen and oxygen (major air components) are absorbed by condensate and makeup water when exposed to the atmosphere. Thus air and other non-condensable gases are present in the steam and condensate loop.

The presence of air and non-condensable gases impair the performance of steam condensate system. Deposition of air on heat transfer surfaces forms air film that reduces the heat transfer rate. Carbon dioxide is absorbed by feedwater as carbonic acid which decreases the pH level of the boiler feedwater. Heating carbonates and bicarbonates (coming from the water treatment chemical exchangers) in the boiler decompose into caustic soda and also release carbon dioxide that results in corrosion of boiler parts as well as steam and condensate pipework. The solubility of oxygen in feedwater depends on temperature. The higher the temperature of feedwater the smaller is the amount of dissolved oxygen. Oxygen is very harmful and even a small amount of it can cause pitting of metals and other severe damages to the system.

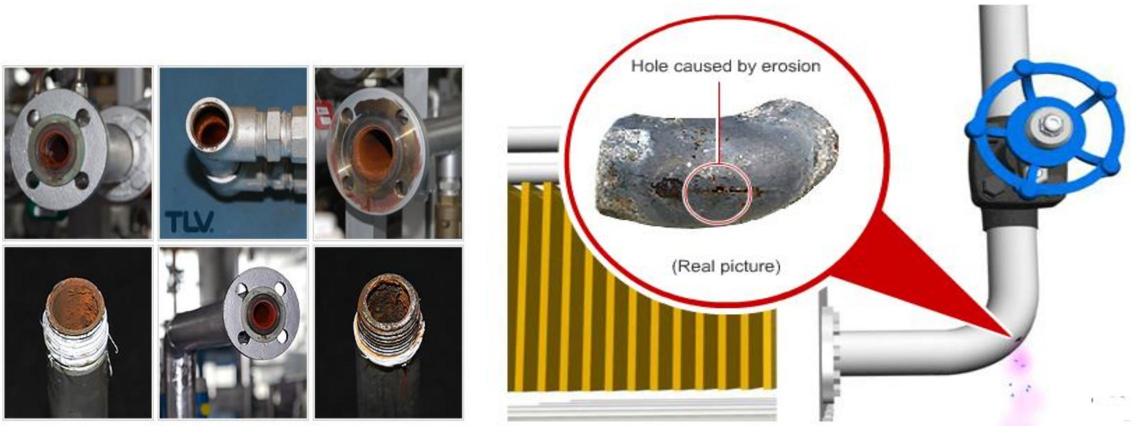
5.4 Corrosion and erosion of steam and condensate pipes

Corrosion is the gradual destruction of a material caused by chemical reactions. The condensate recovery pipes made from steel contain a large amount of iron. When such pipes are exposed to air and water, the oxidation reaction causes iron to rust. Similarly, copper pipes are degraded into copper ions by the condensate having high temperature and low pH values. The dissolved copper ions and rust from the contaminated condensate deposit as solid build-up around the valve seats resulting in valve blockages and temperature reduction in condensate recovery pipelines.

The corrosion of metal pipes starts at the interior surfaces causing pipe thinning and finally leads to pipe failures when not prevented on time. In addition, the recovered condensate containing metal solutes deteriorates water quality and causes scale deposition in the boiler during heating. (TLV, 2017)

Erosion is a physical process that induces gradual wearing of solid via abrasion. The fast moving water through the pipes endangers erosion. This water may be both non-discharged condensate and entrained water in the steam flow. The water while flowing with high velocity through the pipe-bends causes gradual thinning of the pipe wall that leads to holes in the pipe, thus resulting in steam leakage. Also, flash steam in the condensate recovery pipelines causes erosion. The flashing erosion can be detrimental and is associated with undersized condensate return lines. Furthermore, the erosion caused by cavitation results in water hammer.

Both corrosion and erosion work together causing thinning of the piping wall, steam leakage, and clogging valves. Figure 22 (a) shows different pipes affected by corrosion and Figure 22 (b) shows a hole caused by erosion in a steam pipeline contaminated with condensate.



(a) (b)

Figure 22. Pipe corrosion (a) and erosion (b) (TLV, 2017)

5.5 Stall conditions and associated problems

The stall is the condition at which condensate starts accumulating inside a heat exchanger and unable to discharge through a drainage device, such as a steam trap, due to the negative pressure differential. Generally, the stall may occur due to three conditions: the presence of vacuum inside an equipment, constant negative pressure differential, and varying positive to the negative pressure differential.

For proper condensate flow, the pressure at the trap inlet should be higher than the pressure at the trap outlet. Even though the steam systems are designed with positive differential pressure for condensate discharge, the pressure differential across the steam trap is interfered by many factors. For instance, using an inlet temperature control valve can arise negative differential pressure in the trap (trap with outlet pressure higher than inlet pressure), thus resulting in stall conditions. The three major problems caused by stall are the uneven heating temperature, water hammer, and ruptured heaters. Figure 23 shows the tube damage caused by water hammer during stall conditions.

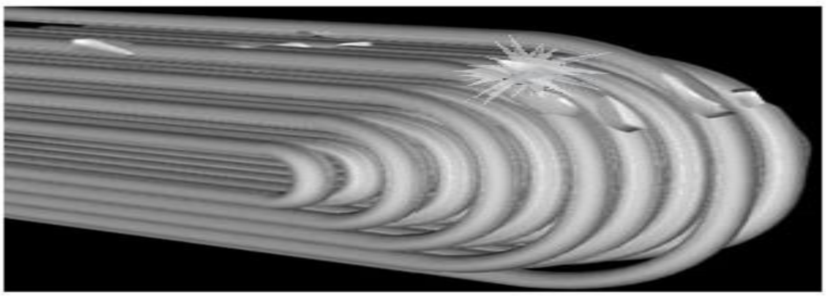


Figure 23. Tubes damaged by water hammer during the stall condition (TLV, 2017)

6 DESIGN CONSIDERATIONS

Condensate systems of steam power plants comprised of several components and pipelines, the detail design of which requires an engineering team having expertise in different areas, such as piping design, pumps, valves, steam traps, flash vessels, and so forth. It is not easy to cover all those features in the present work. However, in this study, some of the most important design parameters and recommendations from the specialists dealing with the design and operation of steam condensate systems are presented.

The piping network of a condensate system consists of horizontal and inclined pipelines. These pipelines can be arranged into three possible ways (options) that are shown below. The horizontal steam pipelines should be sloped downward so that the condensate can be removed easily. Also providing downward slope to horizontal condensate pipelines causes the condensate to flow freely under the gravity. The determination of optimum slope for both horizontal steam and condensate pipelines is an important design parameter and is discussed below. The analysis of condensate flow in upward inclined steam pipelines is carried out with the help of APROS. The prime objective of the analysis is to figure out that at what steam velocity the condensate will change direction and flow cocurrently in an upward inclined steam pipe and what are the influencing factors (see section 7). After exploring recommendations for the slope of horizontal steam and condensate pipelines, this section provides design rules for various components of condensate system as well as explains the importance of several components used in steam condensate system.

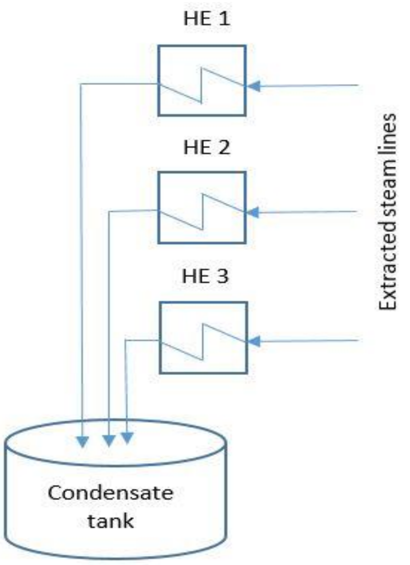
6.1 Efficiency and economics of condensate piping network

Figure 24 shows three options for piping condensate from feedwater heaters (FWHs) to the boiler. Option A is the simplest choice in which the condensate from different FWHs is simply drained into a condensate tank. The condensate from the tank is then pumped to the main condenser, deaerator or boiler. This kind of piping is not only economical (although the condensate tank costs money) but also requires very little attention during operation. However, one of the disadvantages of such piping system is that heat from the hot condensate cannot be recovered and is dissipated in the tank.

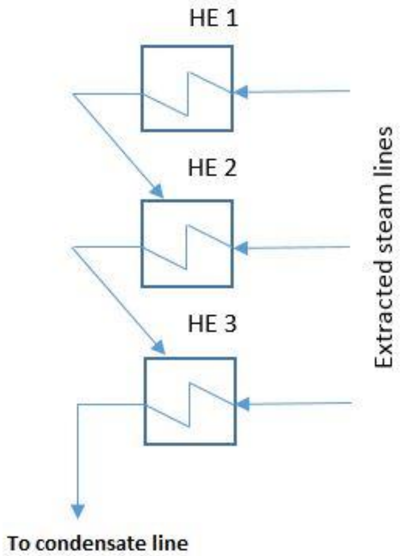
Unlike option A, the heat contained in the condensate is recovered by arranging condensate pipelines according to option B. The hot condensate exiting the higher-pressure FWH is cascaded backward to the lower-pressure FWH in the network, thus transferring heat to the feedwater. The condensate discharging from the lowest pressure FWH is moved either to the boiler or any other storage system in the network. With this type of configuration, heat is recovered from the condensate but the process is not free of problems. The main problem of the arrangement is the huge condensate velocity. As condensate flows from higher-pressure FWH to the lower one, its velocity increases. The condensate flowing with high velocity will damage the piping system as well as feedwater heaters.

In option C, flash vessels are incorporated in the condensate pipelines extending from FWHs. The flash vessels are used to separate flash steam from the condensate. The flash steam is either discharged to the atmosphere or forwarded to the flash steam recovery system. When flash steam is collected in a recovery system, the heat from the steam can be captured. Thus, both in options B and C heat can be recovered. Flashing steam directly to the atmosphere will result in environmental hazards as well as heat losses.

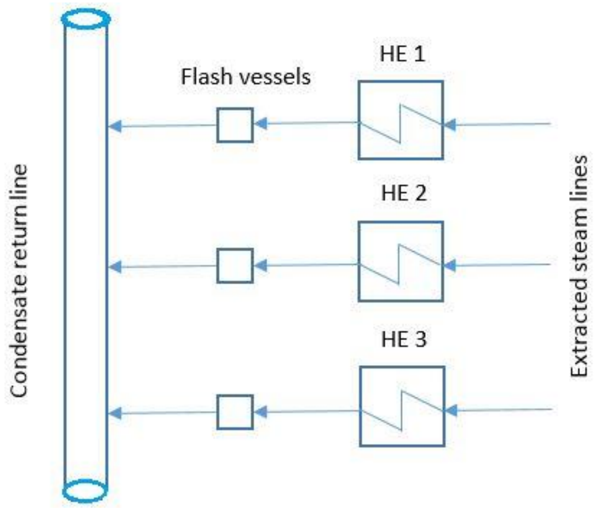
To summarize, arranging condensate piping according to option A will cost less but heat from the condensate cannot be recovered and is dissipated in the tank. With options B and C, heat can be recovered but the piping costs may be higher. Hence, a compromise is always reached between the economics and efficiency while designing the piping network of condensate systems of steam power plants.



(Option A)



(*Option B)*



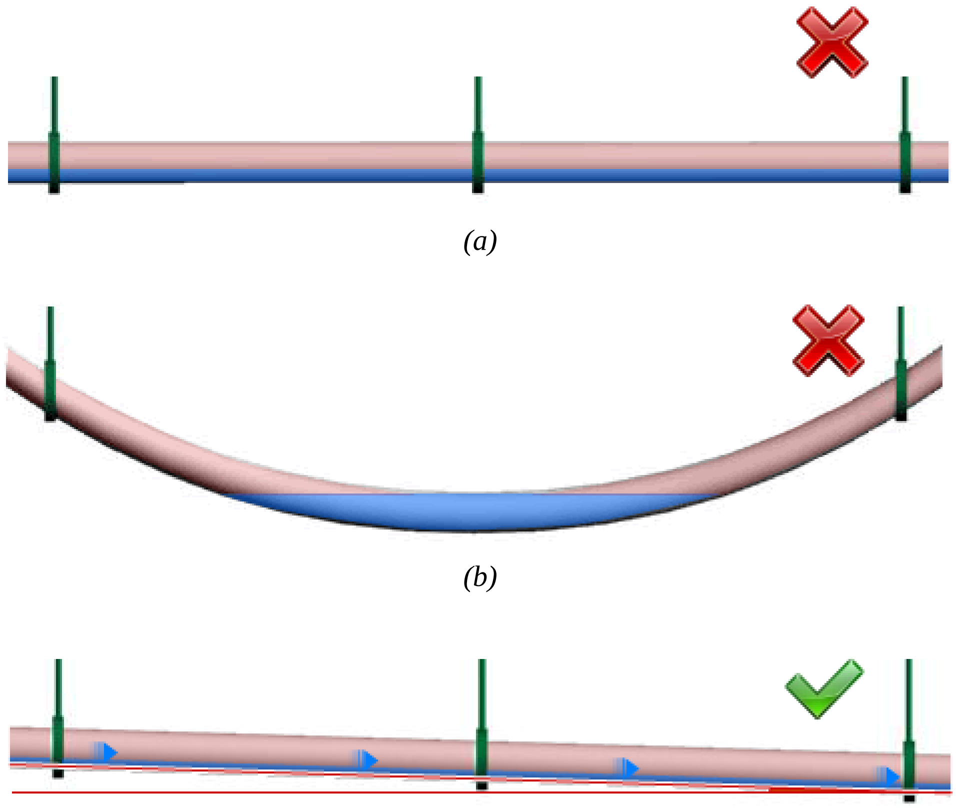
(Option C)

Figure 24. Three options for condensate piping network

6.2 Slope for horizontal steam and condensate pipelines

Condensate pooling that leads to water hammer is caused by many factors, such as inappropriate piping slope (pitch), malfunction of steam traps, concentric reducers, and so on. However, the most dominant among these is the poor piping slope for steam as well as condensate pipelines. The steam pipeline should not be set parallel to the ground as this can impede condensate flow, Figure 25 (a). Also, piping should be supported properly to prevent them from deflection. Figure 25 (b) shows an example of the improperly supported pipeline where the pipe hangers (piping support) are set at long distances causing the pipeline to deflect under its own weight. This will cause condensate to pool at undesired locations even if the piping is slightly sloped downward. Thus the horizontal pipelines of steam and condensate must be properly supported and sloped downward in the direction of flow, Figure 25 (c). This downward slope does not allow the accumulation of condensate within horizontal steam lines and reduces the problem of water hammer that occurs when condensate is carried along the pipe length by high-velocity steam. In addition, this helps in draining the condensate conveniently at specific locations using different steam traps.

Similarly, providing appropriate downward slope to horizontal condensate pipelines assists the condensate to flow freely under the gravity. Many professionals and experts from various fields suggest different slopes for steam and condensate pipelines. In the following paragraphs, some of the recommended slope values are provided.



(a)

(b)

(c)

Figure 25. Piping support and slope for horizontal steam pipelines (TLV, 2017)

The efficiency of steam power plants has been improved through the regeneration process in which certain amount of steam is extracted from the turbine at different pressure levels. The extracted steam is then transported towards feedwater heaters where the temperature of boiler feedwater is increased. The condensate forms within such steam pipelines due to radiation heat loss, during the warm-up period, or while the lines are hot but there is no flow. Therefore, such systems should be carefully designed. There are many standards and guidelines available for designing these systems and a detail description of which can be found in (Mohinder L. Nayyar, 2000). One of the most important guidelines, and which is the subject of this work, is to provide appropriate slope to the extraction steam piping. In the piping handbook (Mohinder L. Nayyar, 2000), it is recommended that the extraction steam pipeline should be given a downward slope of not less than 10 mm/m or 1:100, in the direction of flow. Pipelines that contain steam and condensate mixture or require draining periodically should be sloped downward approximately 20 mm/m or 1:50. This means that steam pipelines containing a large amount of condensate should be provided with a high downward slope in order to remove condensate decently.

There are several other recommendations from various experts that are given in Tables 1 and 2. The suggested downward slopes for horizontal steam pipelines are listed in Table 1, whereas, Table 2 represents some of the proposed downward slopes for horizontal condensate pipelines. Although, there is very slight variation among these slopes, nevertheless, the exact slope for any steam or condensate pipeline can only be figured out by practical experience.

Table 1. Recommended downward slope for horizontal steam pipelines

Recommended slope	Reference
1:200 – 1:300	(Yoshitake, 2017)
1:240 – 1:250	(James F. McCauley, 2000)
1:240	(Xylem, 2012)
1:240	(FCI, 2005)
Not less than 1:100	(TLV, 2017)
Not less than 1:100	(Spiraxsarco, 2005)

Table 2. Recommended downward slope for horizontal condensate pipelines

Recommended slope	Reference
1:240	(ASPE, 2016)
Not less than 1:70	(Spiraxsarco, 2005)
Not less than 1: 70	(Marshall, 2017)

6.3 Sizing discharge line from steam trap

Condensate formed in steam pipelines should be removed to avoid water hammer. The condensate and small amount of steam from the steam main drop into a drip leg, also called drain pocket, from where the mixture moves towards a steam trap. The drain line to steam trap connects steam trap with the drip leg. The steam trap allows only condensate to discharge into a condensate common return line. The connection among drip leg (drain pocket), drain line to trap, steam trap, the discharge line from trap and condensate common return line is shown in Figure 26.

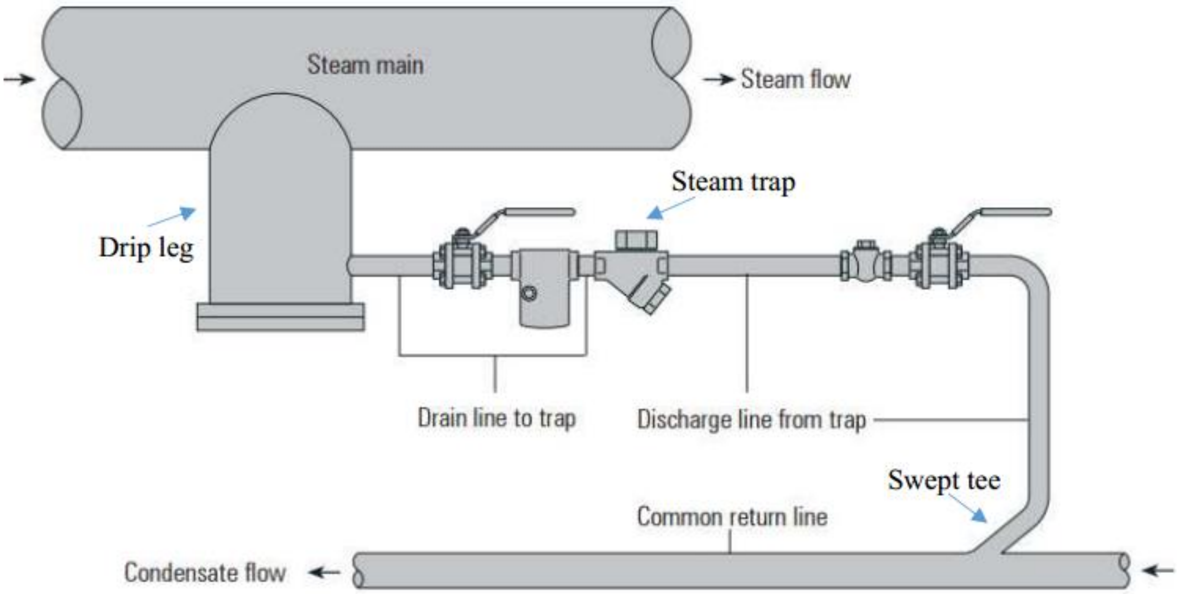


Figure 26. Different components of steam condensate system connecting steam main with condensate return line (Spiraxsarco, 2005)

The discharge lines from steam traps contain condensate and flash steam. The two-phase flow has characteristics of both vapour (steam) and liquid (condensate) in proportion to how much of each is present. Due to the high specific volume of vapour, flash steam occupies most of the space. For instance, consider a system using steam at 5 bar is provided with a mechanical steam trap that drains the condensate at the saturated temperature to the condensate common return line operating at 1.5 bar. The corresponding enthalpies are:

At 5 bar h_f = 640 kJ/kg

At 1.5 bar h_f = 467 kJ/kg and h_{fg} = 2226 kJ/kg

By putting the above enthalpies values in the formula (equation 1) used for calculation of flash steam, the percentage of flash steam will be;

$$\text{Flash steam \%} = (640 - 467) / 2226 \times 100$$

$$\text{Flash steam \%} = 7.8\ \%$$

And the percentage of condensate in the flow will be (100 - 7.8 = 92.2) 92.2 %.

For 1 kg of condensate discharging into the above-mentioned condensate return line, the corresponding masses of flash steam and condensate will be 0.078 kg and 0.922 kg, respectively. At 1.5 bar the saturated water density is 950 kg/m^3, thus the volume occupied by 0.922 kg of condensate will be (0.922/950) 0.001 m^3. Similarly, the volume of steam can be determined using the steam table. At 1.5 bar the specific volume of steam is 1.159 m^3/kg, so the steam will occupy a volume of (0.078 × 1.159) 0.090 m^3. The total volume occupied by the mixture will be (0.09 + 0.001) 0.091 m^3.

This means that;

Water (condensate) will occupy = 0.001/0.091 × 100 = 1.1 % space

Steam will occupy = 0.09/0.091 × 100 = 98.9 % space

It follows that most of the space is occupied by flash steam, and condensate occupied very small volume. Hence, the discharge line from steam trap should not be designed according to the relatively small volume of condensate. The undersized line will result in increased flash steam velocity and back pressure that can lead to many problems, such as water hammer, flooding of the piping network, and reduced steam trap capacity.

Steam pipelines are sized based on the maximum velocities. The velocity of dry saturated steam should not exceed 40 m/s, whereas, the velocity of 15 – 20 m/s is recommended for the wet steam pipelines, (Spiraxsarco, 2005) and (Marshall, 2017). The wet steam flowing at lower velocities will minimize the erosion and damaging effects to the piping fittings and valves. The discharge lines from steam traps can be considered as steam lines carrying very wet steam and thus should be sized according to the aforementioned recommended low velocities (15 – 20 m/s). This will help in maintaining the desired pressure and velocity values in the condensate network.

6.4 Keep drain line to trap short and provide fall in flow direction

The drain line to trap is the pipeline that connects a steam using equipment or drip leg (as shown in Figure 26) with a steam trap. The line contains condensate as well as steam. Figure 27 shows that longer drain line to trap should be eliminated as it can be filled by steam that halts the condensate flow towards the steam trap. This phenomenon is known as steam locking and results in condensate accumulation within the pipework that ultimately leads to the problem of water hammer. Thus it is advantageous to keep such lines as short as possible, ideally less than two metres.

In circumstances where it is impossible to use short drain lines, the problem of steam locking can be controlled by using float type steam traps with steam lock devices. Such traps restrict the flow of live steam to the condensate lines. Furthermore, the drain lines to traps should be given appropriate downward slope that assists condensate to flow freely under gravity.

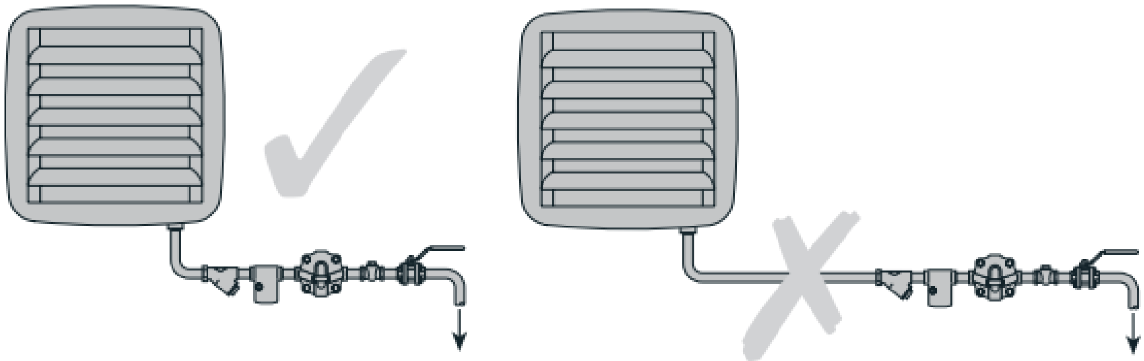


Figure 27. Keep drain line to steam trap short (Spiraxsarco, 2005)

6.5 Use swept tee to reduce the effects of blast discharges

One of the major disadvantages of thermodynamic and inverted bucket type steam traps is the associated blast discharges from these traps. The blast discharges result in high velocities and mechanical stresses in the condensate piping network. For this purpose, swept tee should be used between the steam trap and condensate common return line, as shown in Figure 26. By doing so, the mechanical stresses and erosion problems are reduced at the points where the drain line from steam trap joins the common condensate return line. Thus the failure rate of the pipes will be lowered.

In situations where thermodynamic and inverted bucket type traps are not the final design requirements, the problem of blast discharges can also be handled by using other types of steam traps, such as thermostatic traps and mechanical float traps.

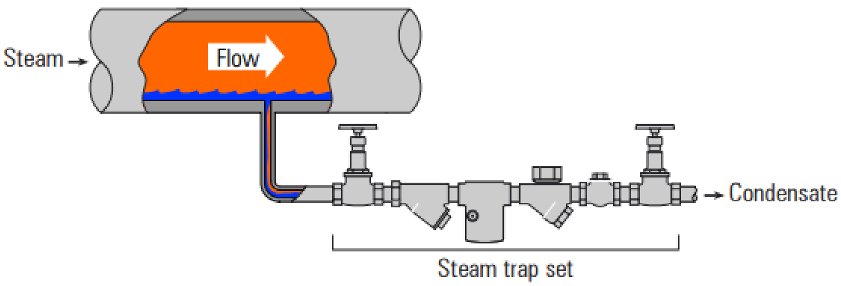
6.6 Size and location of drip legs

Drip legs or drain pockets are used to drain condensate and non-condensate gases from steam pipelines. The condensate within such pipelines moves in a number of ways. At start-up and low pressure, the amount of condensate is large creating a gravity flow condition. Under moderate steam velocities, the large amount of condensate moves along the perimeter of piping. When the condensate is low and steam velocity is high, the condensate becomes entrained in steam. Thus the variation in condensate flow conditions throughout the operation cycle makes the location and design of drip legs vital for proper removal of condensate from steam pipelines.

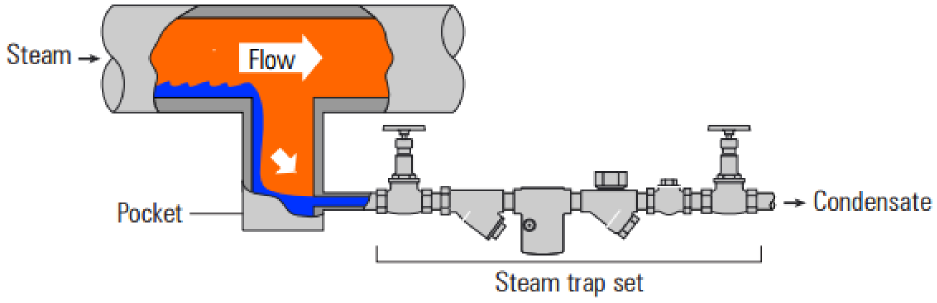
Drip legs must be placed at the end of steam mains, at risers (preferably beyond the point of change in direction), and ahead of pressure-reducing valves, temperature regulators, expansion joints, bends, and separators (Armstrong, 2011). The proper placement and sizing of drain legs will reduce the number of problems that are mistakenly considered as unavoidable. These include water hammer, steam leaks resulting from pipe erosion, short equipment life, reduced heat transfer rate and long start-up times, (FCI, 2005).

Recommendations about drain legs placement can be found in the literature. The (Spiraxsarco, 2005) suggests installing drain pockets on larger steam mains at intervals of 30 m to 50 m. In the reference (James F. McCauley, 2000), it has been stated to fit drip legs at approximately 45 – 90 m intervals. In addition, the (Armstrong, 2011) recommends installing drip legs at about 90 m intervals along the steam mains.

The design of drain pocket is equally important. The high-velocity steam will drag the condensate along the steam pipeline and cause water hammer when the drain pocket is not of appropriate size, as illustrated in Figure 28. Figure 28 (a) shows an undersized pocket where a very little amount of condensate enters into the pocket while most of it passes over the drain pocket connection. On the other hand, Figure 28 (b) shows an appropriately sized pocket where all the condensate flows into it. Thus for adequate removal of condensate, drain pockets should be sized properly.



(a)



(b)

Figure 28. Undersized and properly sized drain pocket (Spiraxsarco, 2005)

According to (James F. McCauley, 2000), the diameter of the condensate collecting drip legs should be the same as the steam mains up to 100 mm size. For larger steam mains, the collecting legs can be 2 or 3 sizes smaller than the main but not less than 100 mm. The length of the legs with the automatic start-up of the plant is usually 700 mm or more. With the supervised start-up, the length of the legs can be the same or half of the steam main diameter but not less than 200 mm.

For the configuration shown in Figure 29, the (Spiraxsarco, 2005) suggests sizing of drain pockets according to the dimensions listed in Table 3. For steam mains with the diameter (D) up to 100 mm, the pocket diameter (d_1) should be the same as the steam main and the depth of the pocket (d_2) not less than 100 mm. With steam mains diameter of 125 mm to 200 mm, the pocket diameter should be 100 mm and its depth at least 150 mm. For steam mains with larger diameters, 250 mm and above, the pocket diameter should be half of the main while its depth should be the same as the steam main diameter.

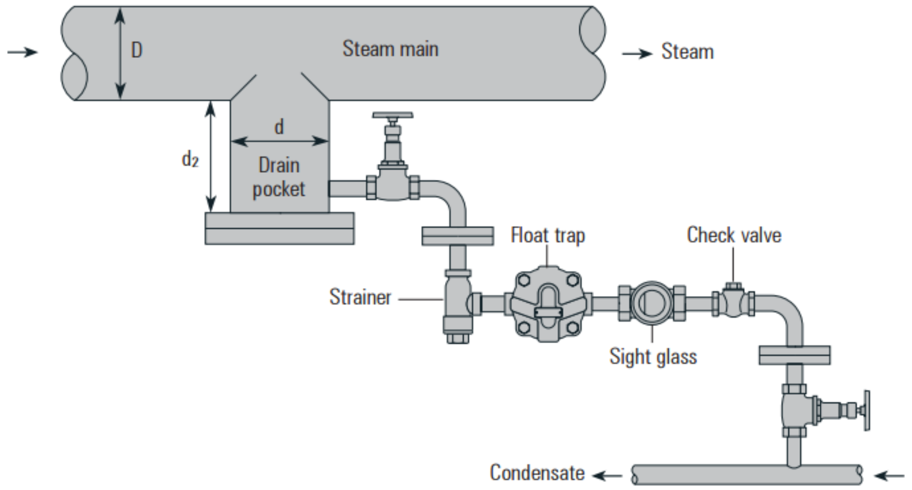


Figure 29. Drain pocket dimensions (Spiraxsarco, 2005)

Table 3. Diameter and depth of drain pocket (Spiraxsarco, 2005)

Main diameter D	Pocket diameter d_1	Pocket depth d_2
Up to 100 mm	$d_1 = D$	Minimum d_2 = 100 mm
125 mm – 200 mm	d_1 = 100 mm	Minimum d_2 = 150 mm
250 mm and above	$d_1 = D/2$	Minimum $d_2 = D$

The (Armstrong, 2011) uses a slightly different configuration for defining the length or depth of drip legs, as shown in Figure 30. The distance of steam trap from the steam main is defined as the length of drip leg. Table 4 indicates the steam main size and the corresponding length and diameter of drip leg. For small diameter mains (up to 450 mm), the length of the drip leg for the cases supervised warm-up and automatic warm-up are different, but for larger diameter mains (500 mm and above), the drip leg length should be the same for both cases. In the supervised warm-up, the valve is opened manually to trap the system, whereas, the valve opens automatically in the automatic warm-up. The diameter of drip legs should be designed the same way as recommended by (Spiraxsarco, 2005).

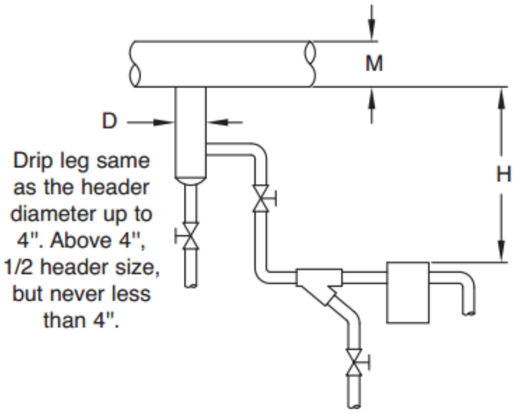


Figure 30. Trap draining drip leg on steam main (Armstrong, 2011)

Table 4. Steam main and drip leg dimensions (Armstrong, 2011)

M	D	H	
Steam main size (mm)	Drip leg diameter (mm)	Drip leg length min. (mm)	
		Supervised warm-up	Automatic warm-up
Up to 100	D = M	250	700
100 – 200	D = 100	250	700
300 – 450	D = M/2	450 – 675	700
500	D = M/2	750	750
600	D = M/2	900	900

6.7 Use two hand valves to ease maintenance

Figure 29 shows two hand valves have been used with a steam trap set for removal of condensate from a steam main. These valves not only help in maintenance but also prevent loss of steam and condensate from pipelines. For example, the two hand valves are closed at the same time when the steam trap set needs repair or replacement. The hand valve near to the drain pocket stops the downward flow of steam and condensate from the steam main, and the second hand valve near to the condensate pipe prevents the backflow of condensate. Hence, there is no need to drain the upstream steam main or the downstream condensate pipeline for any kind of maintenance. Also, air cannot enter the pipelines. Thus the steam and condensate are not wasted and the air prevention assists in keeping proper pressure and temperature both in steam and condensate pipelines.

When only one hand valve is used, either the steam main or condensate pipeline has to be drained during the maintenance. The processes of drainage, keeping the drain and pumping it back consumes time and energy. In addition, air can enter the pipelines or system and impair the plant performance. Therefore, it is rational to use two hand valves instead of one.

6.8 Use sight glass to ensure condensate removal

Figure 29 shows the usage of sight glass after the steam trap. The sight glass helps to ensure the removal of condensate from the steam pipeline or steam using equipment. Also, flow meters can be used for this purpose, however, sight glasses are cheaper, require less or no maintenance, easy to install and work even in the polluted environment. The condensate flow through sight glass can be easily noticed.

6.9 Length of non-pumped rising condensate lines

In situations where it is impossible to avoid the non-pumped rising lines, as shown in Figure 31, the length of the rising condensate pipelines should be kept as minimum as possible. Longer non-pumped rising lines will result in pressure losses and when pressure decreases, some of the condensate changes into flash steam as explained in section 3. Also when the pressure is not enough, the condensate in such lines will not flow upward. A non-turn valve should be provided to prevent condensate from falling back down to the steam trap.

In order to prevent the backward flow of condensate from the common condensate return line into the non-pumped rising line, the rising condensate line should be connected to the top of overhead common condensate return line. Furthermore, it is recommended to use a slightly larger diameter riser. This will decrease the flash steam velocity in the pipe and thus the problems of water hammer and noise will be reduced.

6.10 Sizing pumped condensate pipelines

Figure 31 shows a typical configuration of pumping condensate from the condensate receiver (vented receiver) to the high-level condensate main. The size of the pumped condensate lines is dependent only on the pump discharge rate. The pump starts and stops according to its needs, thus there is no continuous flow in a pumped return line. This can result in situations where discharge rate from the pump is higher than the rate at which condensate enters the pump. Hence, the size of the pumped condensate pipelines should be calculated on the basis of pump discharge rate, not on the rate at which condensate enters the pump. When these pipelines are designed according to the flow rate of condensate entering the pump, then this will result in the following two possible scenarios.

In the first scenario, the discharge lines from the pump will be bigger than required. This will be the case when the condensate flow rate entering the pump is greater than the pump discharge rate. Consequently, the piping cost will be higher because larger pipes are costly.

In the second scenario, the calculated discharge lines from the pump will be smaller than needed. This will be the case when the incoming condensate flow rate is lower than the pump discharge rate. The smaller sized pipes result in huge pressure loss and condensate velocity.

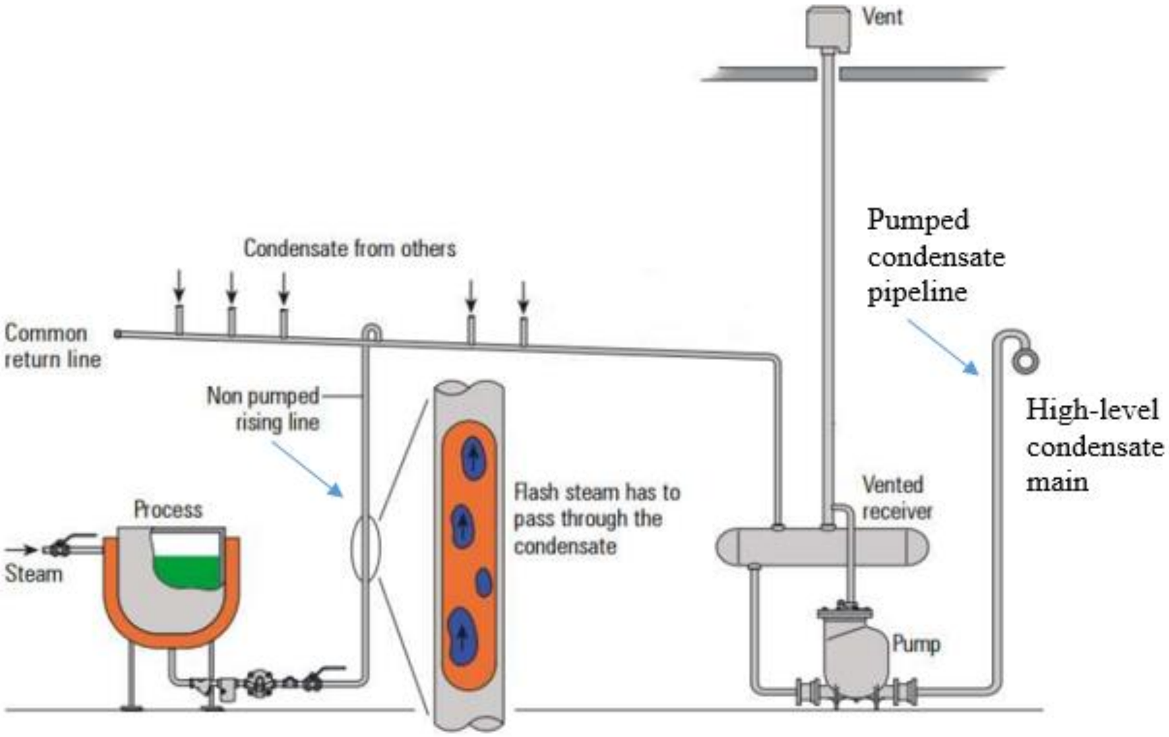
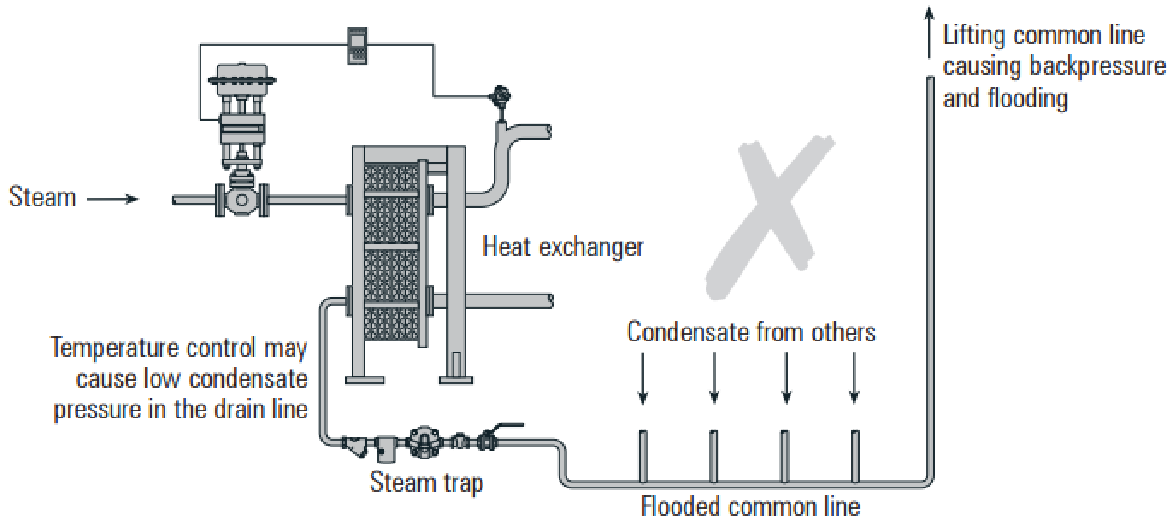


Figure 31. Non-pumped and pumped rising condensate lines (Spiraxsarco, 2005)

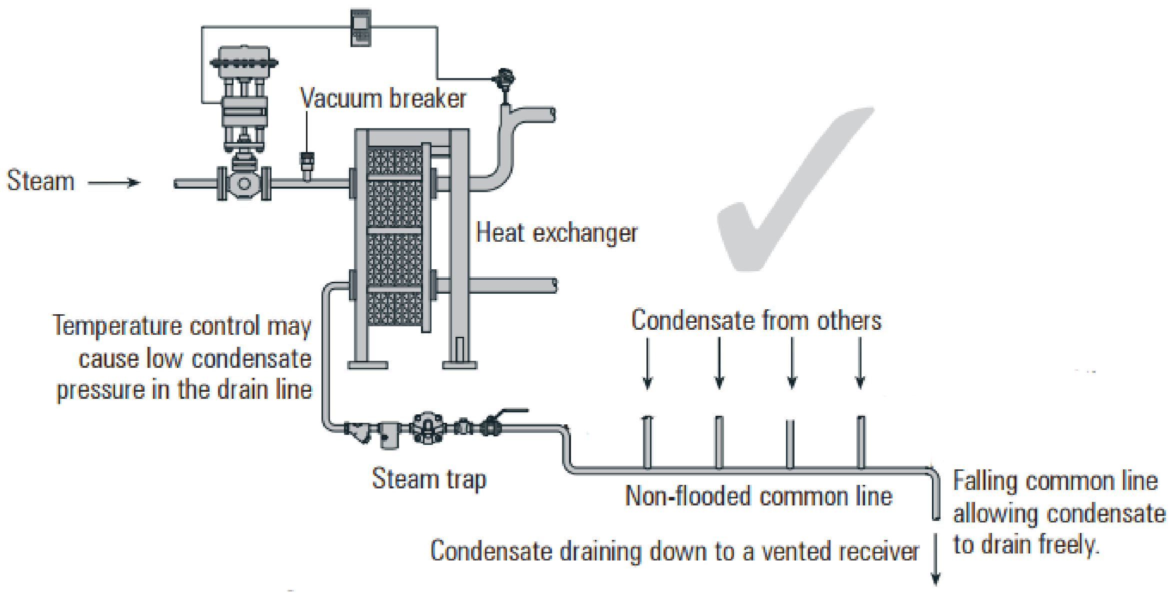
6.11 Provide falling common condensate return lines

For temperature control processes the supply steam pressure is throttled over a control valve. This reduces the capacity of the steam trap to a point where condensate flow stops completely (due to zero pressure gradient) and causes the system to stall. The system stalls when the steam pressure is not enough to remove condensate from the system, and most frequently it occurs in situations where the system operation is changed from full-load to part-load. This results in back pressure and flooding in the common condensate line, thus deteriorating the steam trap performance and impeding the heat transfer capability of the process, such as feedwater heating process, as shown in Figure 32 (a).

In order to minimize the back pressure and prevent the system from stalling, the piping network should be provided with falling common condensate line that will allow condensate to drain freely. Figure 32 (b) shows that falling common line prevents the condensate system from stalling and assists in condensate drainage.



(a)



(b)

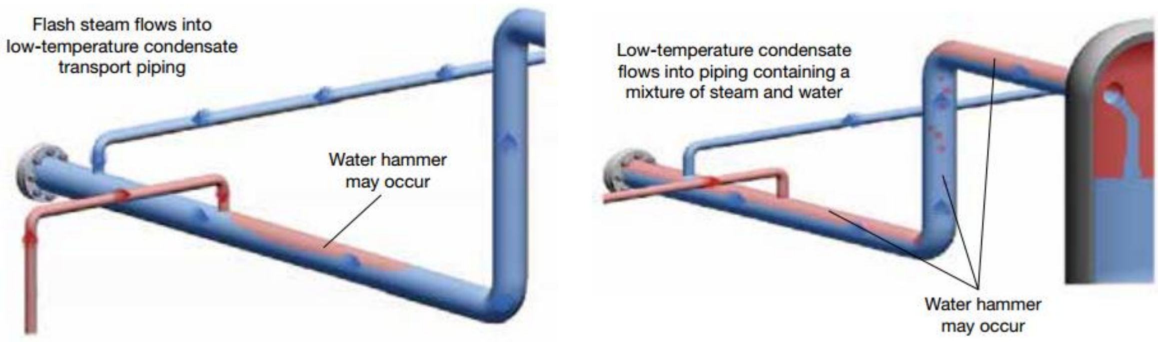
Figure 32. Lifting and falling common condensate lines (Spiraxsarco, 2005)

6.12 Use flash vessel to mitigate water hammer

The existence of flash steam in the condensate pipelines causes water hammer, as discussed in section 5. Figure 33 (a) shows that water hammer occurs when flash steam flows into low-temperature condensate transport piping. Water hammer may also happen when low-temperature condensate flows into piping containing a mixture of steam and water, Figure 33 (b). To simplify, the combination or coexistence of condensate and flash steam causes water hammer in the condensate piping network.

This problem of water hammer can be remedied by installing flash vessels at suitable locations on lines containing the mixture of steam and condensate. Figure 34 shows such an arrangement where a flash vessel is connected to a steam trap discharge line from one side and a condensate transport piping from the other side. The condensate containing flash steam when enters the flash vessel settles at the bottom of the vessel, due to high-density, whereas, the low-density flash steam moves upward and is discharged from the vessel. Furthermore, flash vessels are also employed in situations where it is impractical to install larger condensate return lines. The larger condensate return lines reduce the adverse effects of water hammer by decreasing the velocity of flash steam.

The flash steam from these vessels is either released to the atmosphere or transferred to a flash recovery system for reuse. Recovering flash steam helps in improving the overall efficiency of the plant.



(a) *(b)*

Figure 33. Flash steam causing water hammer in the condensate pipelines (TLV, 2017)

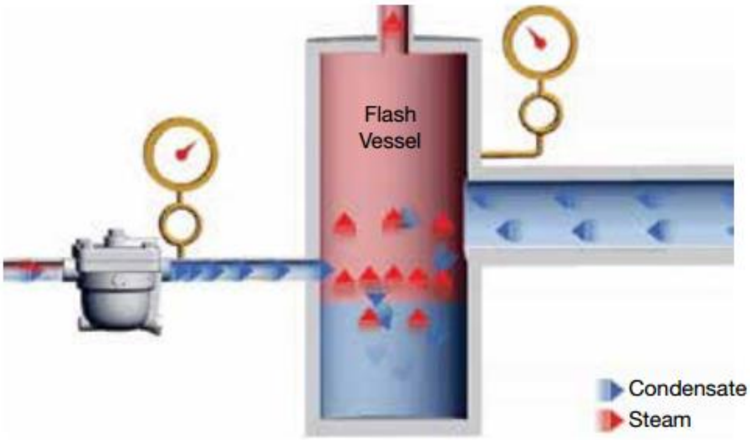


Figure 34. Flash vessel reduces water hammer (TLV, 2017)

As discussed in section 3 (effect of pressure reduction on condensate) that pressure reduction causes some of the condensate to change into flash steam and the resulting mixture (condensate + flash steam) has high volume. This huge increase in volume within the pipe results in high velocities (50 – 60 m/s). The discharge lines from steam traps contain a mixture of condensate and flash steam that flows with high speed. These lines are drained into the flash vessel, which is used to separate flash steam from the condensate, as shown in Figure 34.

Figure 35 shows a flash vessel is connected with a discharge line from steam trap carrying a mixture of condensate and flash steam (from the left side) and a common condensate return line (from the right side). The fast flowing mixture of flash steam and condensate through the discharge line from steam trap contains water droplets that cause erosion of the vessel walls on impact. The eroded vessel is either repaired or replaced with a new one. Both of these options are expensive and difficult to perform.

The problem can be eradicated by placing an impingement plate within the vessel. The high-velocity water droplets exiting the discharge line from steam trap will strike with the impingement plate and erode it only. Thus the walls of the vessel are prevented from erosion in this way. The impingement plate can be fastened or welded inside the vessel, according to the piping connection, and is easy to replace as it is a non-pressure part. The maintenance of pressurized parts, such as the flash vessel, is laborious and carried out by the maintenance team according to the schedule.

Furthermore, the pressure drop through the steam trap should be as close to the flash vessel as possible. On the upstream side, the steam trap is connected with a high-pressure steam pipeline or steam using equipment, whereas, it is connected with the flash vessel operating at lower pressure on the downstream side. The lower pressure line connecting steam trap with the vessel has high-velocity flow, due to the formation of flash steam, which can damage the piping system and other equipment. Thus the pressure reduction should be made near to the flash vessel to avoid high velocity in the pipelines.

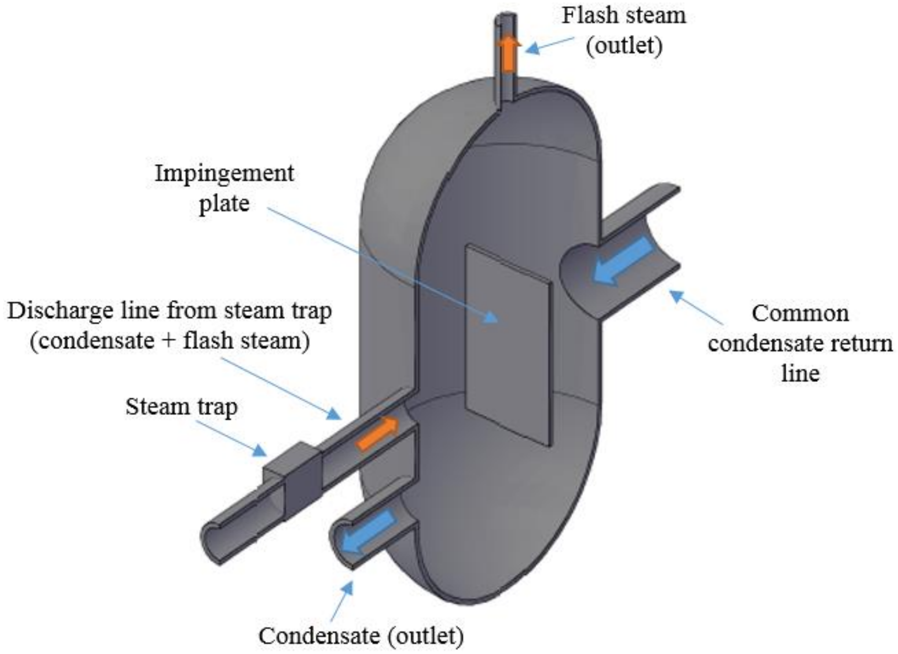
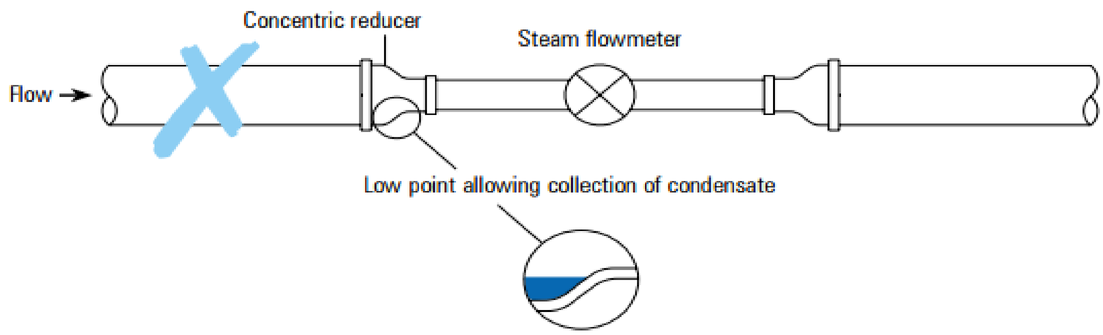


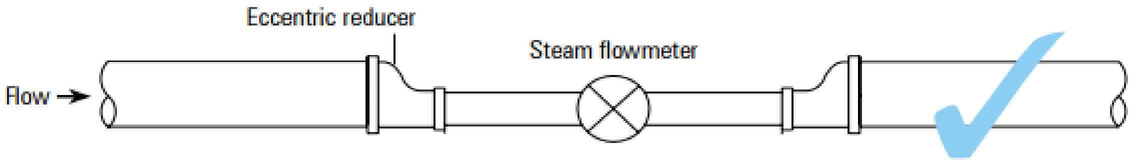
Figure 35. Flash vessel with impingement plate

6.13 Use eccentric reducers for flowmeters and pipe fittings

Figure 36 (a) shows the problem of condensate accumulation at lower points when concentric reducers are used for installing steam flowmeter on a stem pipeline having the diameter larger than the flowmeter. Thus eccentric reducers should be employed in situations where flowmeters are smaller than the pipelines into which they are to be fitted. This will avoid the accumulation of condensate at lower points, as shown in Figure 36 (b).



(a)



(b)

Figure 36. Concentric and eccentric reducer for fitting steam flowmeter (Spiraxsarco, 2005)

Similarly, condensate may also collect and cause water hammer due to improper fittings. Figure 37 shows concentric reducer and eccentric reducer fittings for steam piping. In the concentric reducing fitting, the smaller and larger ends are concentric (having the same centre point). The problem with this fitting type is that water traps on the larger diameter side and cannot travel uphill on its own. The collected water will not be able to flow properly through the rest of the piping and thus will cause water hammer.

Unlike the concentric reducer fitting, the smaller and larger ends of the eccentric reducer fitting do not have the same centre point. But they have the same bottom point creating a smooth bottom that allows the condensate to flow properly through the piping, thus reducing the problem of water hammer.

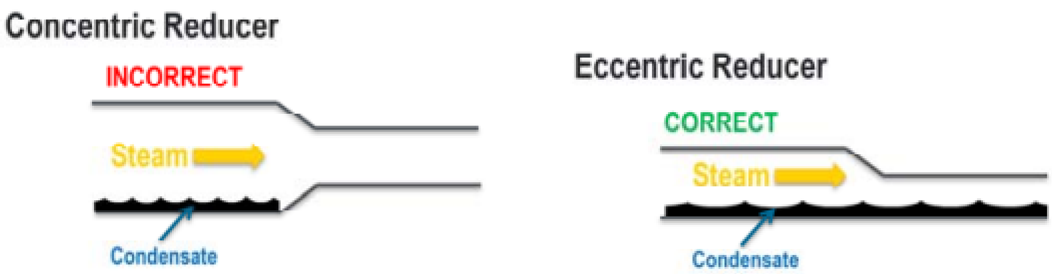


Figure 37. Concentric and eccentric reducer fittings for steam piping (Energy, 2011)

6.14 Take branch line connections from the top of steam main

When branches are taken from the middle or bottom of the steam main, the accumulated condensate and debris will flow into the steam branch and negatively affect the performance of the steam using equipment, Figure 38 (a). Thus the branch line should be taken from the top of the steam main. The driest steam is separated this way and is directed to the point of application, as shown in Figure 38 (b).

Also, it is beneficial to install a valve on the branch as near to the off-take as possible. This will reduce the chances of condensate staying in the branch line when the plant is to be shut down for longer periods.

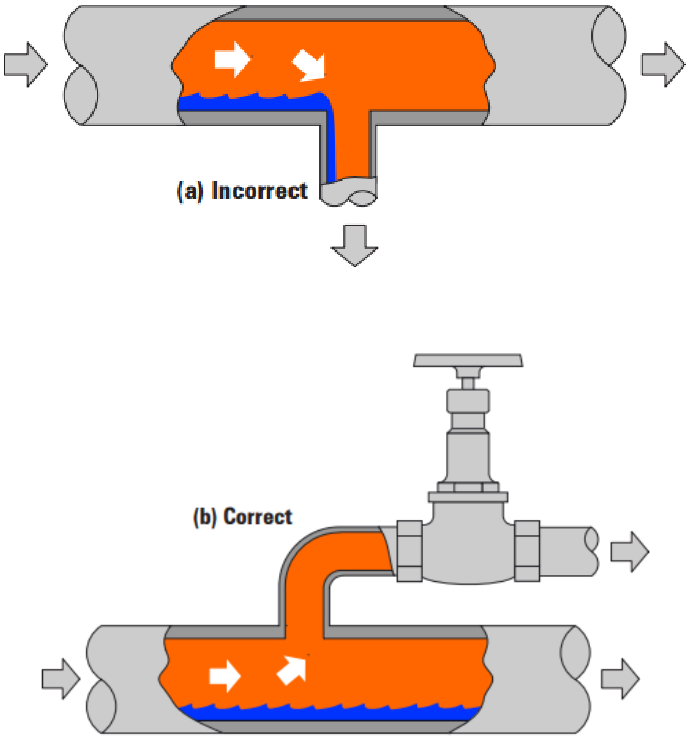


Figure 38. Branch connection from steam pipeline (Spiraxsarco, 2005)

6.15 Provide expansion allowance for hot steam and condensate pipelines

Pipes are usually installed at ambient temperature. However, pipelines carrying hot condensate and steam are operated at higher temperatures and thus vulnerable to expansion, especially in length. This expansion produces stresses at various points of the distribution system that lead to fractures of the pipes and pipe-joints. The amount of expansion can be determined using the following equation.

$$\text{Expansion (mm)} = L \times \Delta T \times \alpha \qquad (2)$$

Where,

L is the length of the pipe between anchors (m)

ΔT is the temperature difference between ambient and operating temperatures (°C)

α is the expansion coefficient (mm/m °C × 10^{-3})

The expansion coefficient α depends on pipe material and temperature. Different materials expand at different rates and tables have been developed that can be used to find out the expansion coefficient for a pipe at the specific temperature.

The pipe expansion can also be read from various charts made for different pipe materials. For example, a 100 m carbon steel pipe distributing steam at 250°C and ambient temperature of 15°C will expand 330 mm in length as indicated on the chart (Figure 39) developed for steel pipes.

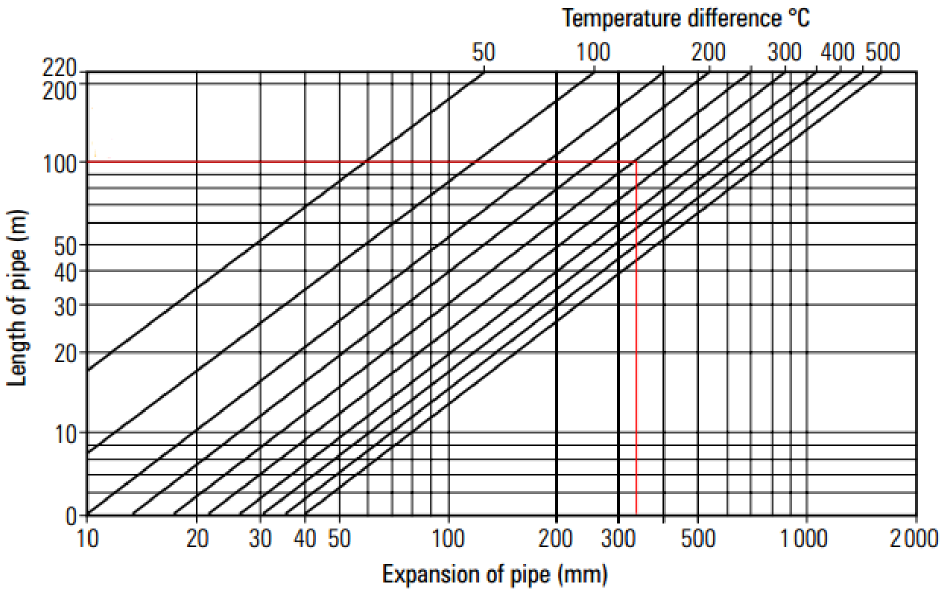


Figure 39. Expansion chart for steel pipes (Spiraxsarco, 2005)

7 TWO-PHASE FLOW IN UPWARD INCLINED STEAM PIPELINES

Figure 40 shows condensate changing flow direction from countercurrent to cocurrent as the steam flow rate (steam velocity) is increased in an upward inclined steam pipe. In the absence of steam, the condensate flows downward through the pipe, (a). As steam is introduced, a small amount of condensate changes its direction and starts flowing with steam, (b). By further increasing the steam flow rate, more condensate travels in the reverse direction from the point of injection, (c) and (d). Finally, at certain steam flow rate cocurrent flow develops in the pipe and all the condensate flows upward with steam, (e). (Hewitt, 2010), (Gregory W. Zysk, 2010), (Moon-Hyun Chun, 2000) and (Wongwises, 1998) have explained the phenomenon of condensate flow reversal in two-phase (gas-liquid) flows.

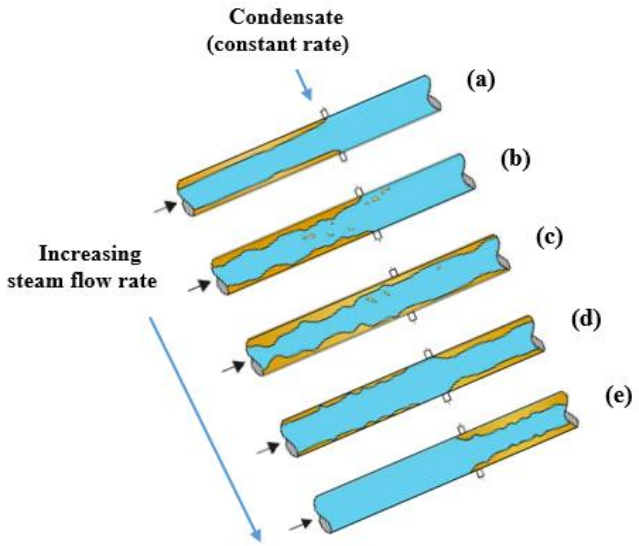


Figure 40. Condensate flow reversal in upward inclined steam pipe (Hewitt, 2010)

For the design of condensate piping networks, it is important to understand the direction of condensate flow in upward inclined steam pipelines. When condensate flow direction is not known, drain points are chosen wrongly and thus condensate cannot be properly discharged from such pipelines. This section deals with the analysis of two-phase (steam-condensate) flow in an upward inclined steam pipe using APROS. The objective of the analysis is to determine at what steam velocity the condensate in the pipe will flow upward cocurrently with the steam. The various factors, such as length of the pipe, the diameter of the pipe, pipe inclination, temperature and pressure difference between the pipe inlet and outlet, affecting the flow are also investigated.

7.1 Introduction to APROS models

The three main thermal hydraulic models in APROS software are the three-equation or homogeneous model, the five-equation model, and the six-equation model. All these different models are one-dimensional (1D) using the staggered grid. The power plant models are managed with 5 or 6 equation models on the primary side and the 3 equation model on the turbine island sections. The six-equation model is the recommended tool for detailed engineering and safety analysis containing a wide range of parameters and provides iterative solution methods. Thus in this work, the six-equation model is used for the analysis of two-phase (steam-condensate) flow in the upward inclined steam pipe. The WS (water-steam) is selected as the fluid for the branches and pipe used in the modelling.

The six-equation model of APROS is based on 1D conservation equations of mass, momentum, and energy. These equations when applied to the liquid and gas phases, a total of six partial differential equations are used which are discretized with respect to space and time. These equations can be found in (Markku Hänninen, 2012). Also, reference (Siikonen, 1987)contains the principles required for the numerical solution of six-equation model. Furthermore, the six-equation model uses different correlations that vary according to the flow regime. The flow regimes managed by the model are as under:

- The bubbly flow having a low void fraction. The void fraction (volume fraction of gas phase) is 1 for flows containing gas only and is 0 for pure liquid flows.
- The annular flow having high void fraction. In such flows, the liquid phase forms a film on the surface of the flow channel.
- The droplet flow having high void fraction. However, in such flows the liquid phase exists as droplets.
- The stratified flow where the liquid and gas phases exist as separate layers.

In addition to different correlations utilized for different flow regimes, there are various weighting coefficients, such as void fraction, the rate of stratification and rate of entrainment, that are used in situations where a smooth transition between flow regimes is required. A discussion about these weighting coefficients is available in (Markku Hänninen, 2012).

For the present model, the stratified flow is considered with the assumptions that the liquid (condensate) and gas or steam (vapour) phases will flow as two separate streams through the pipe and there is no heat loss (adiabatic process) from the pipe. The assumed pipe is an upward inclined superheated steam pipe with a constant flow rate of condensate (saturated water) flowing in opposite direction to the steam (countercurrent steam-condensate flow) due to gravity. The objective of the modelling is to figure out that at what steam velocity a certain mass flow rate of condensate will be pushed uphill by the steam (resulting in cocurrent steam-condensate flow) against the gravity.

7.2 Description of flow model

Figure 41 shows the APROS model developed for the aforementioned flow. The model can be divided into five different sections. The section “Superheated steam inlet” consists of a Point and a Branch. The surrounding red lines mean that both the Point and Branch are excluded from the simulation. The pressure (p), temperature (T), elevation (Elev) and void fraction (α) of the inlet superheated steam are varied from the properties of the Point (PO03), and the steam mass flow rate (fG) can be changed from the properties of the Branch (BR01). The section “Upward inclined steam pipe” consists of an upward inclined steam pipe (PIP01) where two-phase (steam-condensate) flow occurs. The inclination of the pipe is changed by changing the Elev of the Point (PO04). The mass flow rate of condensate and steam flowing through this pipe are represented by fL and fG, respectively. The section “Superheated steam outlet” consists of a Branch and a Point. The mass flow rates of steam and the condensate pushed uphill by the steam can be seen from the properties fG and fL of the Branch (BR02). The pressure, temperature and void fraction values of the outgoing steam are varied by the properties of the Point (PO02). This Point is also excluded from the simulation. The section “Saturated water (condensate) inlet” consists of a Point and a Branch that are excluded from the simulation (surrounding red lines). The pressure, temperature, elevation and void fraction of the injected condensate is varied by the properties of the Point (PO05). The property fL of the Branch (BR03) is used to change the mass flow rate of the injected condensate into the inclined steam pipe (PIP01). The section “Saturated water outlet” consists of Points, Branch and a Valve. The purpose of the check valve (CHV01) is to stop negative flow in order to prevent the pressure drop in the loop. The pressure, temperature, elevation and void fraction properties of the Point (PO06) can be changed according to the flow requirements. This point is also excluded from the simulation.

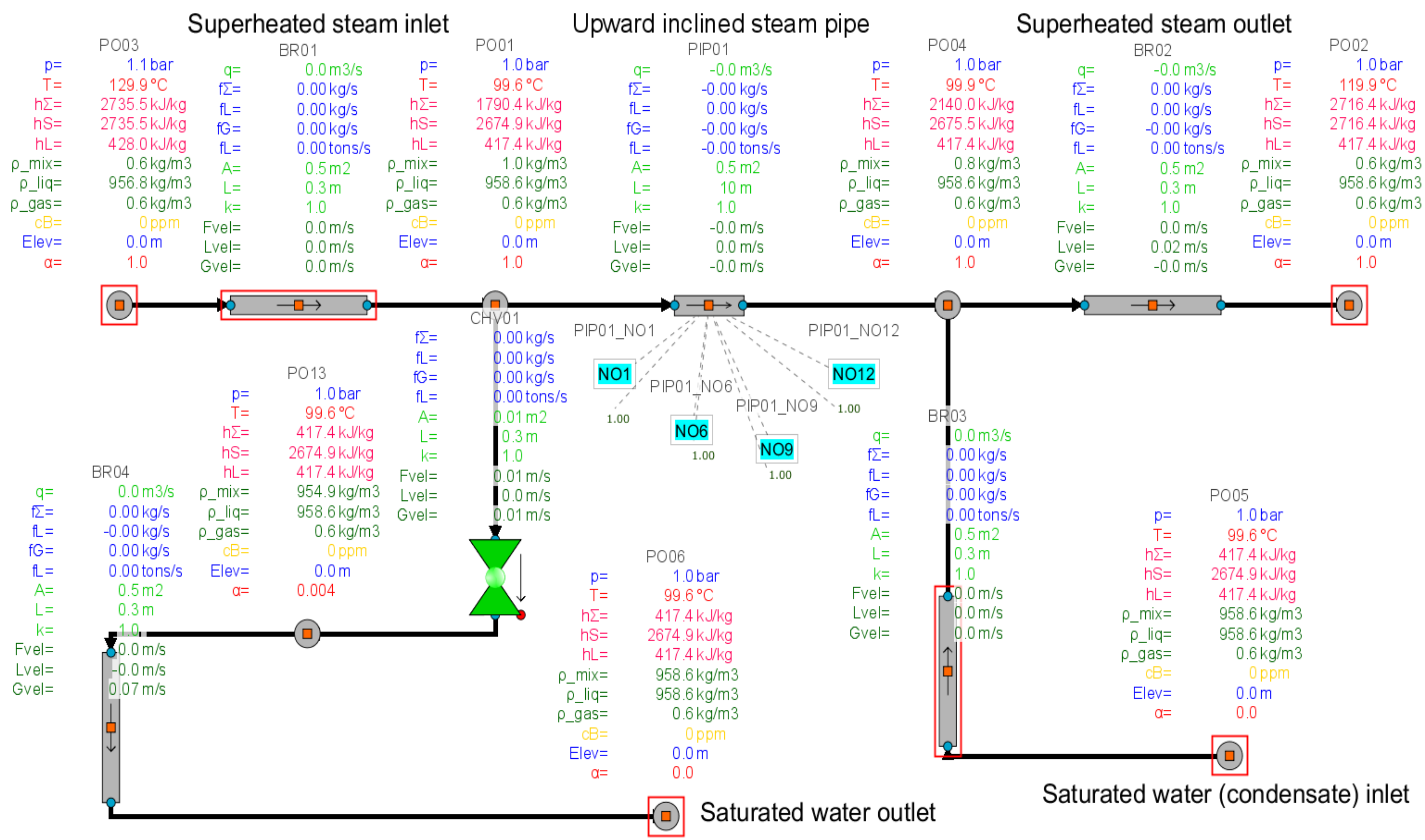


Figure 41. APROS model for two-phase (steam-condensate) flow in upward inclined steam pipe

7.3 Defining component attributes

In order to simulate a fully developed stratified flow through the upward inclined steam pipe, different attributes for the Branches, Points, Pipe, and Valve were defined. For all the Points, the six-equation model was chosen among the various flow models available. The WS (water-steam) was selected as the flowing fluid. Thus, the Branches, Pipe and Valve connected with these Points had the same flow model (six-equation) and fluid (WS). The void fraction (α) was set 1 for the Points (PO03) and (PO02) and 0 for the Points (PO05) and (PO06). The length of the Branches (L) was kept constant as 0.3 m, however, their areas (A) were changed according to the Pipe area (same flow areas were used for Branches and Pipe during each simulation). The length and area of the Valve were kept constant as 0.3 m and 0.01 m^2. A total of 12 nodes (NO1 to NO12) were selected for the Pipe (PIP01). For the Branches and Pipe mostly default values of attributes were used except the following: CCFL_CORRELATION, UPDATE_DIRECTION and BR_SEPAR_OPT. The first two attributes are common to both Branches and Pipe, however, the attribute BR_SEPAR_OPT is specific to Branches only. The different options selected for these attributes are given below, and a detail discussion can be found in the reference (Markku Hänninen, 2012).

- CCFL_CORRELATION: This attribute defines the interfacial friction correlation. The possible values are 0, 1, 2, 3, 4, 5, 6, and 7. The value 0 means the default correlation for pipe geometry is used (the one which was chosen for all simulations presented in this study). Values 1–4 mean alternative corrections developed for rod bundle geometry. Value 5 & 6 are used for the analyses of nuclear reactors. Value 7 means a large interfacial friction coefficient is used to ensure that the liquid and gas phases have the same velocity.
- BR_SEPAR_OPT: This attribute defines the phase separation assumptions applied in the junctions. The available options are 0, 1, 2, 3, and 4. For the present analysis, the option 1 was selected which means that no phase separation was wished in the junction, both gas and liquid had the same velocity.
- UPDATE_DIRECTION: This attribute defines the direction where values of variables describing the state of the pipe are updated during simulation. In this analysis, the value 2 was used which means that the mixture mass flow was updated from the inclined steam pipe to the branch.

7.4 Running a simulation

Before running a simulation, only superheated steam was introduced into the system that increased the void fractions at both ends of the inclined steam pipe (PO01 and PO04). Then after a certain period, the mass flow rate of the steam was set 0 (BR01, fG = 0.00 kg/s), as shown in Figure 41. The figure depicts the initial conditions of the model used for each simulation before the injection of condensate. In this case, the superheated steam at pressure (p) of 1.1 bar, temperature (T) of 129.9°C and void fraction (α) of 1 is introduced into the system, section "Superheated steam inlet" (PO03). At the section "Superheated steam outlet" (PO02), the pressure, temperature and void fraction have been set at 1 bar, 119.9°C and 1, respectively. As there is no condensate injected (BR03, fL = 0.00 kg/s) at the section "Saturated water (condensate) inlet", the void fraction is 1 both at the outlet (PO04) and inlet (PO01) of the "Upward inclined steam pipe". Also throughout the inclined steam pipe (NO1 to NO12), the void fraction is 1 ($\alpha = 1$). Furthermore, the elevation of all the Points was set 0 (Elev = 0).

Next, the condensate was injected into the system, as shown in Figure 42 (in this case, BR03, fL = 0.50 kg/s). In the absence of steam and at elevation of 1 m (PO05, PO04, PO02), due to gravity the injected 0.50 kg/s of condensate flows downward (countercurrent) through the inclined steam pipe (PIP01, fL = -0.50 kg/s), the check valve (CHV01, fL = 0.50 kg/s) and finally through the Branch (BR04) at the section "Saturated water outlet".

Then steam was introduced into the system that pushed the condensate uphill, resulting in a cocurrent flow. This can be seen in Figure 43 where 1.10 kg/s of steam (BR01, fG = 1.10 kg/s) is required to cause 0.50 kg/s of condensate flow uphill (BR02, fL = 0.50 kg/s). It should be noted that in APROS it is the steam and condensate mass flow rates (fG and fL) that can be varied, not the velocities. The velocities of the liquid (Lvel) and gas (Gvel) are calculated automatically by the APROS code. In this case the corresponding velocity of steam (for fG = 1.10 kg/s) is 3.68 m/s. Thus at this steam velocity, the condensate of 0.50 kg/s will flow uphill, instead of flowing downward in the inclined steam pipe (PIP01).

Figure 44 shows the chart developed for the simulation. It can be seen that condensate changes direction as steam flow rate (velocity) changes and eventually flows cocurrently with steam at a particular steam velocity.

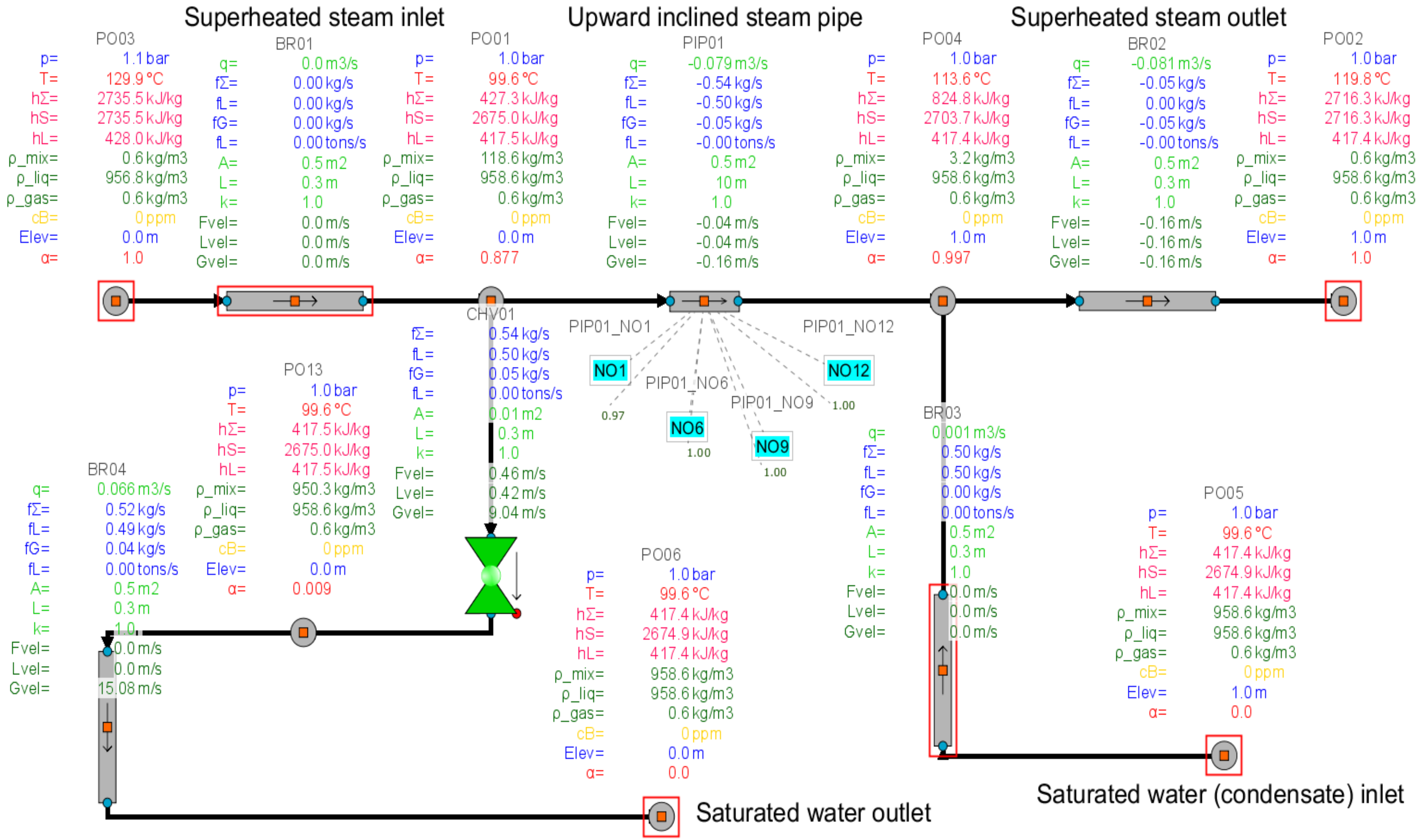


Figure 42. Condensate flowing downward in upward inclined steam pipe when there is no steam flow

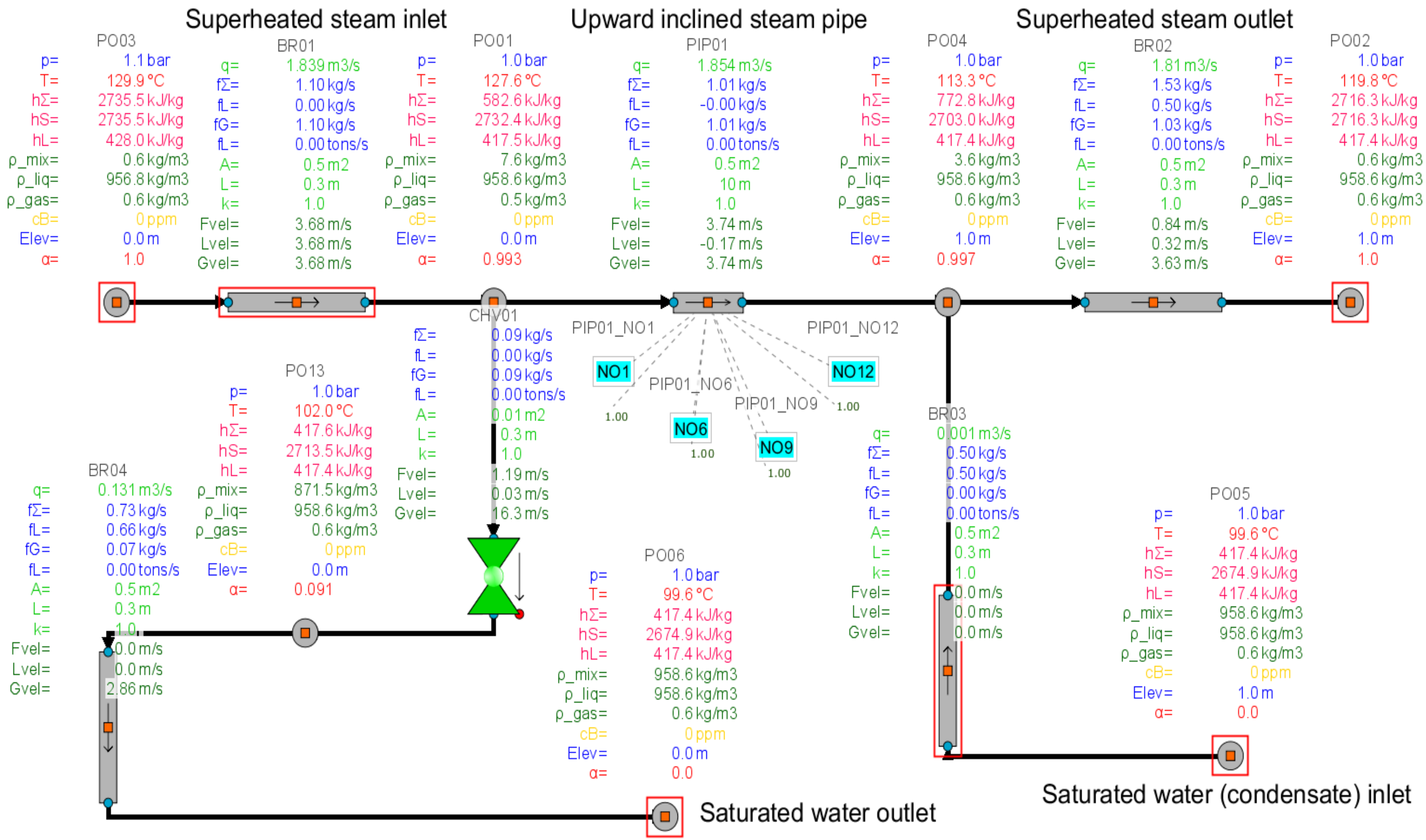


Figure 43. Condensate flowing uphill cocurrently with steam in upward inclined pipe

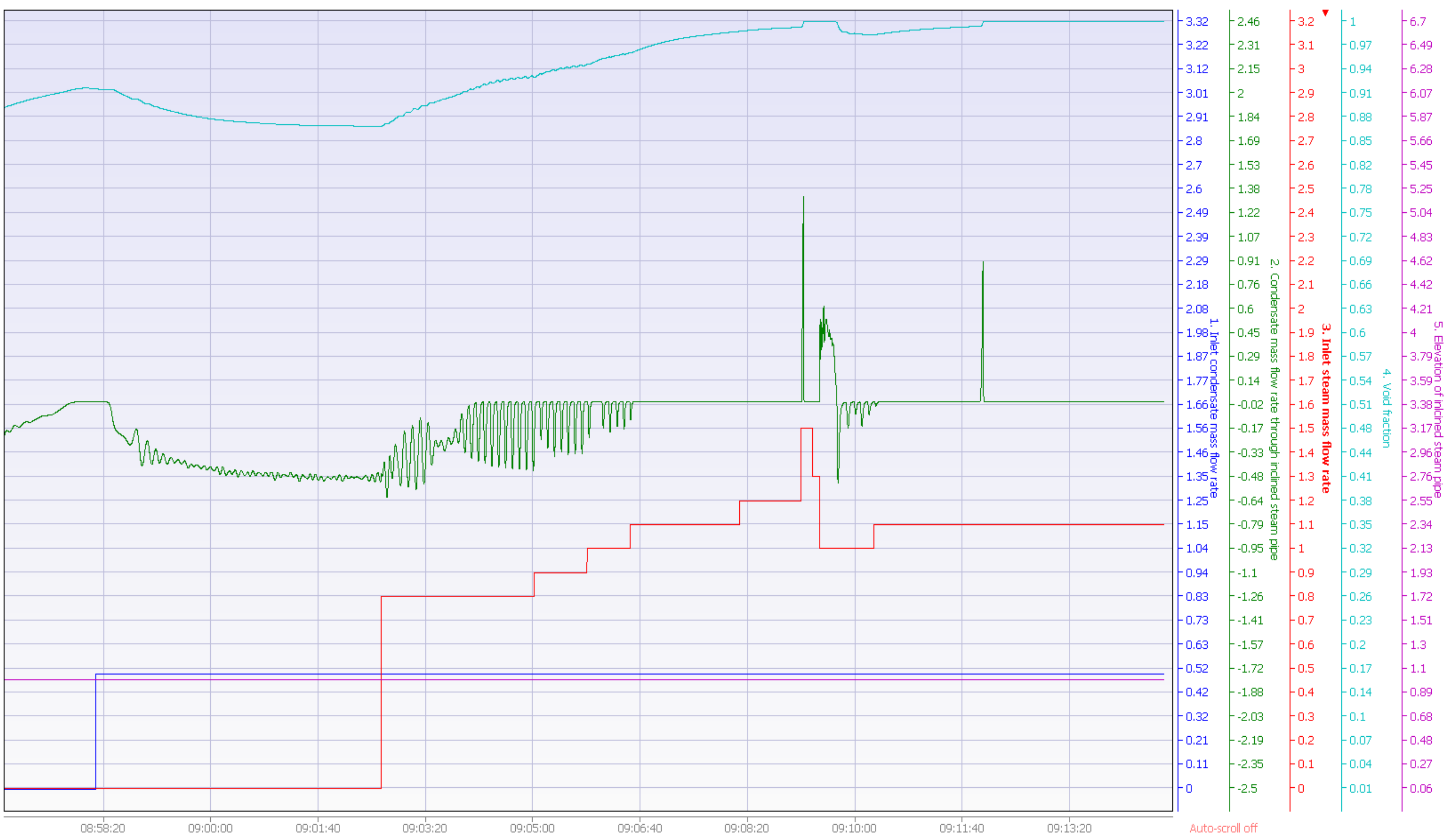


Figure 44. Chart for condensate flow in upward inclined steam pipe

7.5 Results and discussion

A total of 27 simulations were carried out in order to analyse the behaviour of two-phase flow in the upward inclined steam pipe. The steam velocity at which condensate moves uphill depends on many factors. In this study, the effects of the following factors are investigated:

- Length of the inclined steam pipe (5 m, 10 m, 20 m)
- Flow area of the inclined steam pipe (0.08 m^2, 0.3 m^2, 0.5 m^2)
- Elevation of the inclined steam pipe (1 m, 3 m, 5 m)
- Pressure difference between the pipe inlet and outlet (0.1 bar, 0.5 bar)

Length of the inclined steam pipe

Figure 45 shows how the steam velocity (velocity at which the condensate is pushed uphill against the gravity by steam, resulting in cocurrent flow) varies by changing the length of the steam pipe. The graph is obtained for 3 m elevated steam pipe with flow area of 0.5 m^2 and condensate mass flow rates of 0.5 kg/s, 1 kg/s and 1.5 kg/s. The pressure and temperature values at the inlet and outlet of the superheated steam pipe sections respectively are, 1.1 bar and 130°C, 1 bar and 120°C.

By looking at this graph, it can be stated that the steam velocity required to push condensate uphill does not depend on the length of the pipe. The same steam velocity is needed to change the condensate direction through the pipes 5m, 10m and 15m long. However, high steam velocity is needed as the condensate mass flow rate increases.

Flow area of the inclined steam pipe

Figure 46 shows the effects of changing the pipe flow area on the steam velocity causing condensate to move uphill against the gravity. The graph is obtained for 10 m long steam pipe and condensate mass flow rates of 0.5 kg/s, 1 kg/s and 1.5 kg/s. The pressure and temperature values at the inlet and outlet of the superheated steam pipe sections respectively are, 1.1 bar and 130°C, 1 bar and 120°C.

The graph depicts that as the pipe flow area increases, the steam velocity decreases and thus in bigger diameter pipes small steam velocity will cause condensate to flow uphill.

Furthermore, as the condensate mass flow rate increases greater steam velocity is needed to push the condensate uphill.

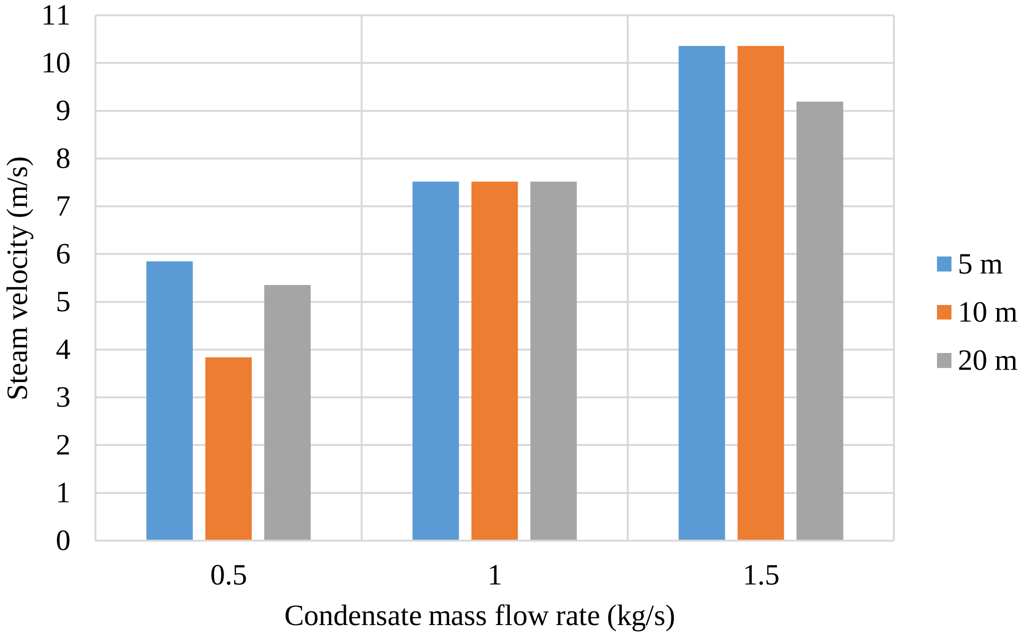


Figure 45. Effect of pipe length on steam velocity needed to push condensate uphill

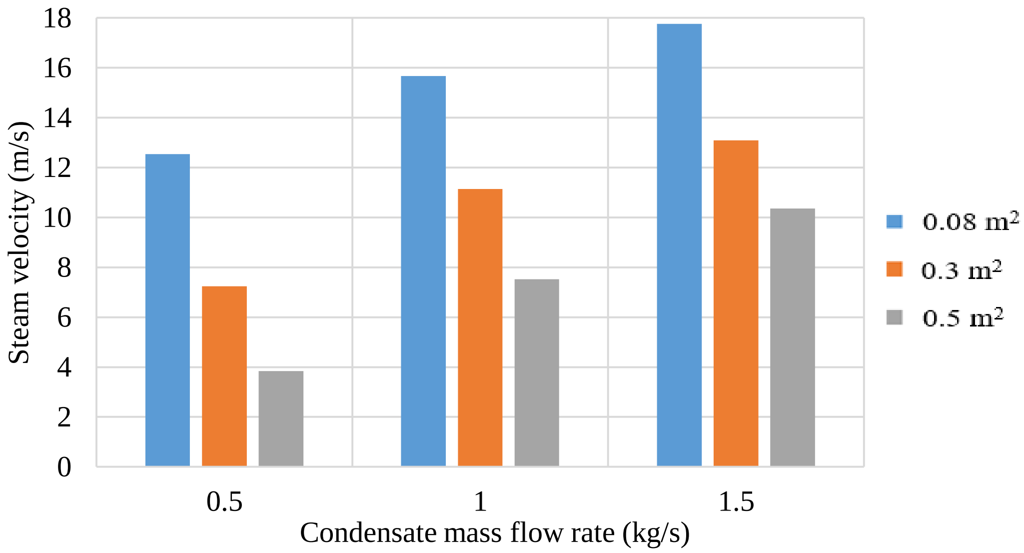


Figure 46. Effect of pipe flow area on steam velocity needed to push condensate uphill

Elevation of inclined steam pipe

Figure 47 shows the effects of pipe elevation on the steam velocity essential for pushing condensate uphill in an inclined steam pipe. The graph is obtained for 10 m long steam pipe with flow area of 0.5 m^2 and condensate mass flow rates of 0.5 kg/s, 1 kg/s and 1.5 kg/s. The pressure and temperature values at the inlet and outlet of the superheated steam pipe sections respectively are, 1.1 bar and 130°C, 1 bar and 120°C.

It is observed that when the condensate flow rate is small, the steam velocity required to push condensate uphill is approximately the same irrespective of the pipe elevation (1 m, 3 m, 5 m). However, as the condensate flow rate increases, the difference among the steam velocity required at different pipe elevation to push condensate uphill also increases. For instance, to reverse the direction of 1.5 kg/s condensate, the steam velocities required at pipe elevations of 1 m, 3 m, and 5 m are 7.86 m/s, 10.36 m/s and 11.2 m/s, respectively. Thus for higher condensate mass flow rates, the steam velocity should be increased to achieve a cocurrent flow in the upward inclined steam pipelines.

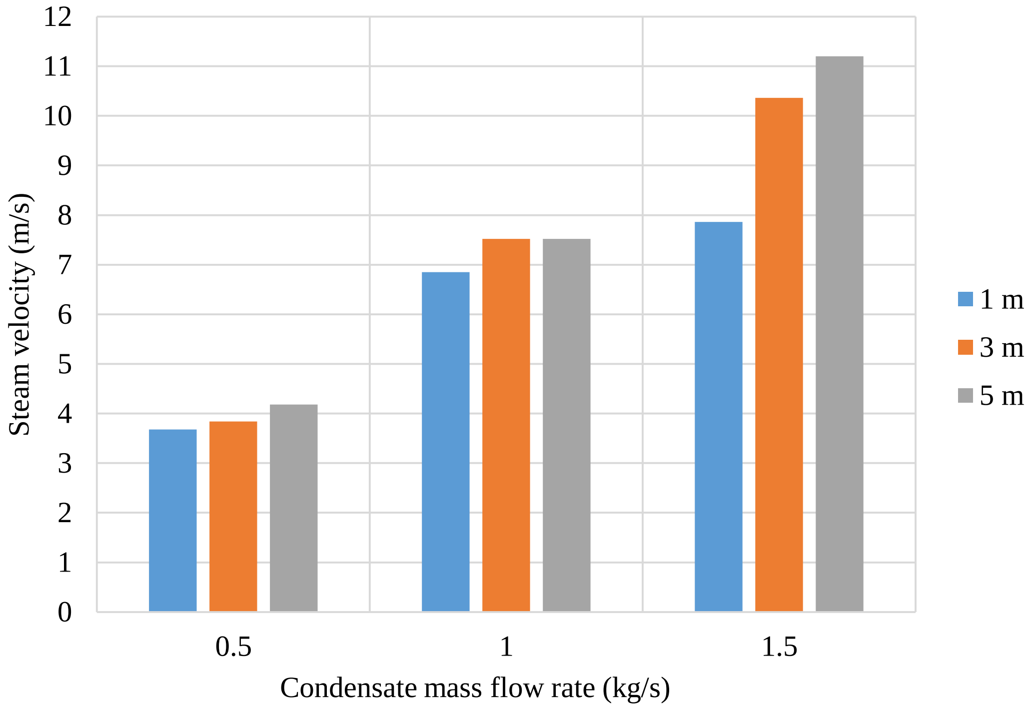


Figure 47. Effect of pipe elevation on steam velocity needed to push condensate uphill

Effects of temperature and pressure differences

Figure 48 shows the effects of the pressure difference between the pipe inlet and outlet on the steam velocity. The graph is obtained for 10 m long steam pipe with flow area of 0.3 m^2 and condensate mass flow rates of 0.5 kg/s, 1 kg/s and 1.5 kg/s. The steam velocity is noted down for the pressure difference of 0.1 bar and 0.5 bar (the temperature difference being constant) between the sections “Superheated steam inlet” and “Superheated steam outlet”.

The graph shows that the lower the pressure drop (pressure difference between the pipe inlet and outlet) in the pipe, the higher will be the steam velocity needed to make a certain amount of condensate flow uphill against the gravity. Furthermore, higher steam velocity is required for larger condensate to flow uphill.

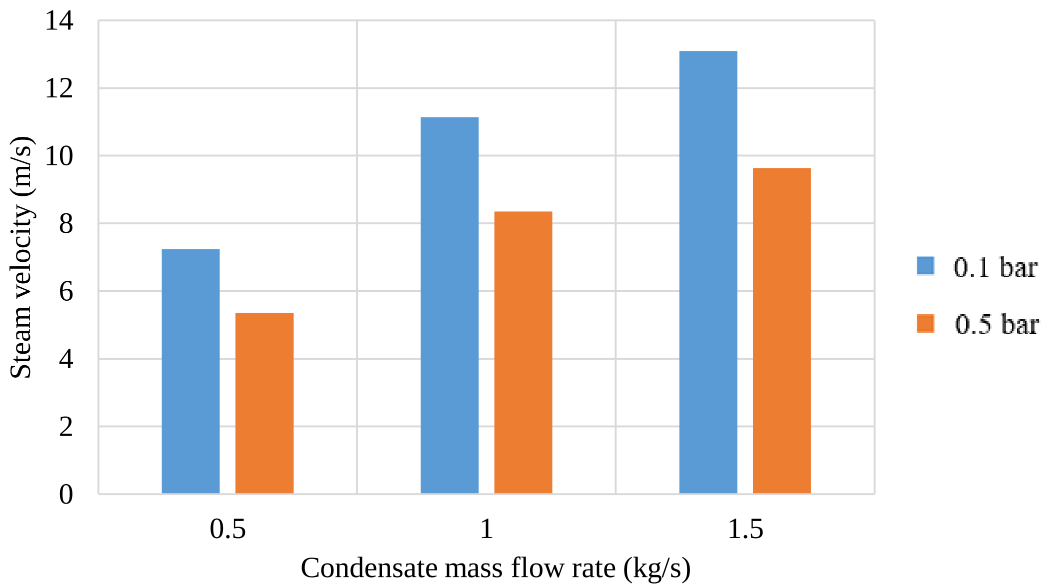


Figure 48. Effect of pressure difference on steam velocity needed to push condensate uphill

Figure 49 shows the effects of the temperature difference on steam velocity. The graph is obtained for 10 m long steam pipe with flow area of 0.3 m^2 and condensate mass flow rates of 0.5 kg/s, 1 kg/s and 1.5 kg/s. The steam velocity is noted down for the temperature difference of 10°C and 30°C (the pressure difference being constant) between the sections “Superheated steam inlet” and “Superheated steam outlet”. From the graph, it can be easily noticed that steam velocity necessary to push condensate uphill remained the same for the temperature difference of 10°C and 30°C. Therefore, steam velocity does not change by changing the temperature difference between the pipe inlet and outlet.

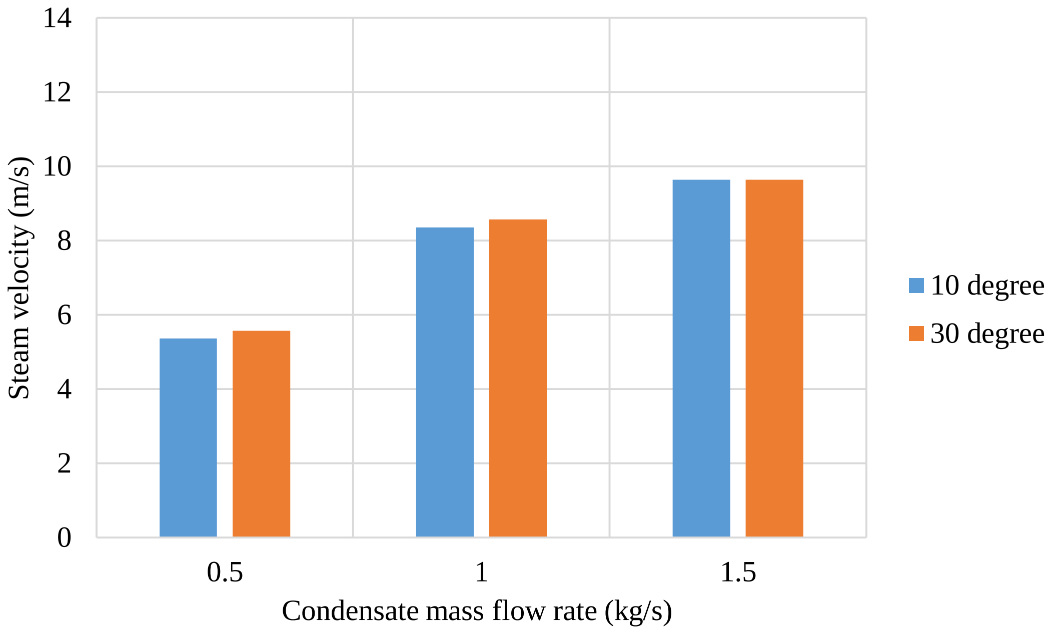


Figure 49. Effect of temperature difference on steam velocity needed to push condensate uphill

7.6 Conclusion

The condensate flow in upward inclined steam pipelines is quite complicated depending on many factors. The effects of pipe length, flow area, elevation, and temperate & pressure difference between the pipe inlet and outlet were analysed in this study. It was observed that the steam velocity causing condensate to flow uphill does not depend on the length of the pipe as well as the temperature difference between the pipe inlet and outlet. The steam velocity is inversely proportional to the pipe flow area and pressure difference (between pipe inlet and outlet). This means that in pipes of larger diameter and with a higher-pressure difference, the condensate reverses flow direction at lower steam velocity. The effect of variation in pipe elevation is negligible at smaller condensate mass flow rates, however, at larger condensate mass flow rates the difference among the steam velocities needed for upward flow of condensate increases. Therefore, it is extremely important to understand the behaviour of condensate (condensate flow direction) in upward inclined steam pipes before installing steam traps for condensate removal.

8 SUMMARY

In regeneration process, fractions of extracted steam from the turbine are used to heat up feedwater in the feedwater heaters. The steam after transferring its enthalpy of evaporation to the feedwater changes into condensate. This condensate is either cascaded backward to the condenser hotwell or pumped forward to deaerator for removing non-condensable gases and further heating. A small amount of condensate also generates in steam pipelines due to radiation heat loss. The hot condensate formed is treated water containing sensible heat and should be recovered for reuse as it accounts for approximately 10% to 30% of the total heat contained by the live steam. Hence, the boiler fuel demand can be reduced from 10% to 20% by economically recovering hot condensate.

The presence of condensate in steam, as well as condensate pipelines, is not free of problems. Accumulation of condensate in steam pipelines results in water hammer that reduces the life of pipework accessories, produces fractures in pipeline equipment and fittings, and causes loss of live steam. Similarly, condensate changes into flash steam in condensate pipelines due to pressure differences. The main problems with flash steam are the huge velocities in the pipelines and formation of vapour clouds that lead to erosion, damaged pipeline fittings, and hazardous working environment.

Thus proper operation of steam condensate system is crucial for the better performance of a steam power plant as it helps to increase the plant efficiency and economics by reducing the boiler heat demand, the failure rate of pipeline equipment and environmental pollution.

Condensate systems of steam power plants comprised of several components and pipelines, the detail design of which requires an engineering team having expertise in different areas, such as piping design, pumps, valves, steam traps, flash vessels, and so forth. It is not easy to cover all those features in the present work. However, in this study the importance of condensate recovery is acknowledged, major components of the system, as well as various problems associated with condensate flow in both steam and condensate pipelines, are discussed. For optimum design of steam condensate system, the study provides some of the most important design parameters and recommendations from the specialists dealing with the design and operation of steam condensate systems.

Importance of condensate recovery

As condensate is treated water and contains heat, its recovery results in significant savings in terms of chemical treatment, boiler fuel demand and environmental hazards. Water requires proper treatment and preparation before it is used in the boiler. The condensate free of impurities can be directly fed into the boiler without any additional treatment, thus avoiding the costs of water treatment and preparation. Supplying hot condensate to the boiler requires lower heat for steam production, hence, the boiler efficiency increases as the fuel consumption decreases. Lower boiler fuel consumption means lower CO_2, NO_x and SO_x emissions, and thus reduced environmental pollution. Furthermore, recovering flash steam (generated from condensate) constraints vapour clouds, decreases noise and hampers water accumulation on the ground and therefore substantially improves the working environment.

Major components of steam condensate system

The processes of handling condensate and feedwater heating and transferring it to the boiler require a complex arrangement of different components, heat exchangers, and pumps, with hundreds of valves interconnected by several kilometres of pipework. Some of the major components of steam condensate system and their importance are discussed.

Steam traps are basically automatic valves that allow condensate and non-condensate gases to discharge from the system while keeping the live steam. The removal of condensate and non-condensable gases avoids many problems in steam pipelines as well as steam using equipment. These traps are capable to differentiate between the live steam and condensate in many different ways and are broadly divided into three main groups, namely; mechanical traps, thermostatic traps and thermodynamic traps. Different applications require different types of traps, the selection of which is dependent on several factors. A good steam trap offers minimum steam losses, long life and reliable, resistive to corrosion, and so on.

Strainers are used to arrest small pieces of debris, such as rust, weld metals and other solid particles, from the steam and condensate systems. Such small particles malfunction valves and components resulting in more downtime and increased maintenance of the plant.

The extraction steam system, heater drains system, heater vents system and condensate dump system of a steam power plant serve different purposes. Extraction steam system is used for preheating feedwater by the extracted steam from the HP, IP and LP sections of the turbine. Heater drains system is used to handle the condensate drains from HP, IP and LP feedwater heaters. The condensate is either drained backward to the condenser hotwell or pumped forward to the deaerator. The purpose of a heater vents system is to remove non-condensable gases from the feedwater heaters and deaerating heater. The condensate dump system is responsible for maintaining a proper level of condenser hotwell.

Problems with condensate flow in steam and condensate pipelines

Flash steam originates in situations where condensate flows from a higher-pressure to a lower-pressure. This phenomenon is mostly happening in pipelines equipped with steam traps. Flash steam produces shock waves and water hammer that damage piping accessories. In addition, when flash steam is released to the atmosphere, vapour clouds are formed that deteriorates the working environment.

Water hammer is of two types, namely condensate-induced and steam-induced. The former is caused by the formation and movement of condensate slugs in steam pipelines. The steam-induced water hammer occurred in condensate pipelines due to the leakage of small amounts of live steam or flash steam. Water hammer can be noticed by the noise and movement of pipes that it produces. Reduced life of pipework equipment, fractures in piping fittings and loss of live steam are some of the serious problems associated with water hammer.

The presence of air and other non-condensable gases in the steam and condensate loop impair the system performance. Air deposition on heat transfer surfaces reduces the heat transfer rate. Carbon dioxide causes pipe corrosion and even a small amount of oxygen in condensate causes pitting of metals. Heating contaminated condensate releases other non-condensable gases that lead to corrosion of boiler parts as well as steam and condensate pipework.

The condensate system is susceptible to the problems of corrosion and erosion. Corrosion is caused by contaminations in the condensate, whereas, erosion results from fast-moving steam and condensate in pipes. Both corrosion and erosion work together causing thinning of the piping wall, steam leakage, and clogging valves.

A stall is a condition at which condensate starts accumulating inside a heat exchanger and unable to discharge through a drainage device, such as a steam trap, due to the negative pressure differential across the drainage device. The three major problems caused by stall are the uneven heating temperature, water hammer, and ruptured heaters.

Design recommendations

Horizontal steam pipelines should not be set parallel to the ground as it impedes the condensate flow. Similarly, providing suitable downward slope to horizontal condensate pipelines assists condensate to flow freely under the gravity. This downward slope does not allow condensate to accumulate within horizontal steam and condensate pipelines thus reduce the problem of water hammer that occurs when condensate is pushed by high-speed steam in pipes. Different specialists recommend different slope for horizontal steam and condensate pipelines, the optimum value of which can be determined by practice. However, the slope of 1:240 is suggested by many professionals.

The direction or behaviour of condensate flow in upward inclined steam pipelines should be acknowledged in advance to deciding the location for steam trap installation. The condensate starts flowing upward cocurrently with steam at a certain steam velocity which depends on many factors. In this work, the analysis of two-phase (steam-condensate) flow is carried out with the help of APROS. It was observed that the steam velocity causing condensate to flow uphill does not depend on the length of the pipe as well as the temperature difference between the pipe inlet and outlet. The steam velocity is inversely proportional to the pipe flow area and pressure difference (between pipe inlet and outlet). This means that in pipes of larger diameter and with higher pressure difference, the condensate reverses flow direction at lower steam velocity. The effect of variation in pipe elevation is negligible at smaller condensate mass flow rates, however, at larger condensate mass rates the difference among the steam velocities needed for upward flow of condensate increases.

The discharge lines from steam traps contain flash steam and condensate. The amount of condensate in these pipes is small and most of the piping space is occupied by the flash steam due to its high specific volume. Such lines are considered as wet steam lines for which the recommended sizing velocity is 15 – 20 m/s. Thus these pipelines should be sized according to the low wet steam velocity instead of the small amount of condensate. This will help in maintaining the desired pressure and velocity values in the condensate network.

The drain lines to steam traps containing condensate and a small amount of leaked live steam can be filled completely with the live steam and thus will prevent the condensate flow when these lines are too lengthy. This problem is called steam locking and can be mitigated by keeping such lines short, ideally less than two metres.

Drain pockets are used to remove condensate and non-condensate gases from the steam pipeline. They are installed at the end of steam mains, at risers and ahead of pressure-reducing valves, temperature regulators, expansion joints, bends, and separators. The proper placement and sizing of these pockets will minimize the problem of water hammer, steam leaks (resulting from pipe erosion), short equipment life, reduced heat transfer, and long start-up times.

To prevent the backward flow of condensate in non-pumped rising condensate lines, the length of such lines should be kept as small as possible. Also using a slightly larger diameter riser will decrease the flash steam velocity, thus reducing water hammer and noise.

The pump used to transfer condensate from the condensate receiver to the high-pressure condensate return lines or boiler does not operate continuously but starts and stops according to its needs. Thus pumped condensate discharge lines should be sized based on the pump discharge rate instead of condensate rate entering the pump.

For temperature control processes, the supply steam pressure is throttled over a control valve. This reduces the capacity of the steam trap to a point where condensate flow stops completely due to zero pressure gradient. This results in back pressure and flooding within the common condensate lines that deteriorate the steam trap performance and impede the heat transfer capability of the process. In order to minimize the back pressure and prevent the system from stalling, the piping network should be provided with falling common condensate lines that allow condensate to drain freely.

The coexistence of flash steam and condensate results in water hammer. This problem of water hammer can be remedied by installing flash vessels at suitable locations. The condensate containing flash steam when enters the flash vessel settles at the bottom of the vessel, due to high density, whereas, the low-density flash steam moves upward and is discharged from the vessel. The flash steam from these vessels is either released to the atmosphere or transferred to a flash recovery system for reuse. Recovering flash steam helps in improving the efficiency of the plant. The flash vessel should be provided with an impingement plate in order to prevent the vessel walls from erosion caused by the fast moving mixture of condensate and flash steam.

Eccentric reducers should be employed in situations where flowmeters are smaller than the pipelines into which they are to be fitted. This will avoid accumulation of condensate at lower points. Condensate may also collect and cause water hammer due to improper fittings. Unlike the concentric reducer fitting, the smaller and larger ends of the eccentric reducer fitting do not have the same centre point but they have same bottom point creating a smooth bottom that allows condensate to flow properly through the system, thus reducing the problem of water hammer.

When branches are taken from the middle or bottom of the steam main, the accumulated condensate and debris flow into the steam branch and adversely affect the system performance. Thus the steam branch line should be taken from the top of the steam main. The driest steam is separated this way and is directed towards the steam using equipment.

Future work

The presence of condensate in steam pipelines causes water hammer that results in reduced life of pipework equipment, fitting fractures and loss of live steam. The condensate from these pipelines should be discharged with the help of separators or steam traps as quickly as possible. In upward inclined steam pipelines, the condensate flow direction changes with the steam velocity. For proper removal of condensate, the direction or behaviour of condensate in such pipelines should be determined in advance to fitting steam traps. Therefore, experimental work should be carried out for the analysis of two-phase (steam-condensate) flow in upward inclined steam pipes in order to understand the effects of different factors on the condensate flow in such pipelines.

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