A multiphase system characterized by the simultaneous existence of several phases, the two-phase system being the simplest case.

- Steam-water flows are two-phase
- Air-water flows are two-component

Some two-component flows (mostly liquid-liquid) consist of a single-phase but are often called two-phase flows in which the term mathematics that describes two-phase or two-component flows is identical, the two expressions will therefore be treated as synonymous.
Topics in the analysis of multiphase systems can include *multiphase flow* and *multiphase heat transfer*.

When all of the phases in a multiphase system exist at the same temperature, multiphase flow is the only concern.

However, when the temperatures of the individual phases are different, interphase heat transfer also occurs.

If different phases of the same pure substance are present in a multiphase system, interphase heat transfer will result in a change of phase, always accompanied by interphase mass transfer.

Combination of heat transfer with mass transfer during phase change is the feature that makes multiphase systems distinctly more challenging than simpler systems.
Based on the phases that are involved in the system, phase change problems can be classified as:

1. solid-liquid phase change (melting and solidification)
2. solid-vapor phase change (sublimation and deposition)
3. liquid-vapor phase change (boiling/evaporation and condensation)

Melting and sublimation are also referred to as fluidification.

Phase change problems can also be classified based on the geometric configurations of the system and the structures of the interfaces that separate different phases.

From the geometric configuration of the system, one can classify multiphase problems as

1. external phase change problems in which one phase extends to infinity
2. internal phase change problems in which the different phases are confined to a limited space.
Multiphase systems can be classified as
1. separated phase
2. mixed phase
3. dispersed phase

Summarized in Table 1.7.

The separated phase case has two phases separated by a geometrically simple interface.

At the other extreme of interfacial complexity are the dispersed phases.

The change of interfacial structure from separated phase to dispersed phase can occur gradually and as a result, there are mixed phases (Cases F through K) in which both separated and dispersed phases coexist.
1.5 Multiphase Systems and Phase Changes

- A multiphase system with separated phases can be considered as a field that is divided into single-phase regions with interfaces between the phases.
- Governing equations for multiphase system with separated phases can be written using the standard local instantaneous differential balance for each single-phase region with appropriate jump conditions to match the solution of these differential equations at the interfaces.
- This interface tracking method, involves solving the single-phase equations in each separate phase.
- Explicit tracking of the interfaces in mixed-phase and dispersed-phases is impossible and even unnecessary.
- In this case, spatial averaging of the governing equations is performed simultaneously over the phases within a multiphase control volume.
- The microscopic detailed interfaces between phases are not explicitly identified.
- Various averaging techniques are often used to obtain nondimensional parameters to correlate experimental data and to obtain flow maps for two-phase pipe flow.
### Table 1.7 Classification of multiphase systems.

<table>
<thead>
<tr>
<th>Type</th>
<th>Case</th>
<th>Typical regimes</th>
<th>Geometry</th>
<th>Configuration</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(a) liquid layer in vapor</td>
<td>(a) filmcondensation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(b) vapor layer in liquid</td>
<td>(b) filmboiling</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(c) solid layer in liquid</td>
<td>(c) solidification</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(d) liquid layer in solid</td>
<td>(d) melting</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(e) solid layer in vapor</td>
<td>(e) sublimation &amp; deposition</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Phase Change on Plane Surface</td>
<td></td>
<td>(a) liquid jet in gas</td>
<td>(a) atomization</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(b) gas jet in liquid</td>
<td>(b) jet condenser</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Liquid-Gas Jet Flow</td>
<td></td>
<td>(a) liquid core and vapor film</td>
<td>(a) filmboiling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(b) vapor core and liquid film</td>
<td>(b) filmcondensation or evaporation</td>
</tr>
</tbody>
</table>

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## 1.5 Multiphase Systems and Phase Changes

<table>
<thead>
<tr>
<th>Type</th>
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<th>Configuration</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separated phases</td>
<td>D</td>
<td>Melting at a single melting point</td>
<td><img src="image" alt="Solid core and liquid layer" /></td>
<td>Melting of ice in a duct</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>Solidification at a single melting point</td>
<td><img src="image" alt="Liquid core and solid layer" /></td>
<td>Freezing water in a duct</td>
<td></td>
</tr>
<tr>
<td>Mixed Phases</td>
<td>F</td>
<td>Slug or Plug Flow</td>
<td><img src="image" alt="Vapor pocket in a liquid" /></td>
<td>Pulsating heat pipes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>Bubbly Annular Flow</td>
<td><img src="image" alt="Vapor bubbles in liquid film with vapor core" /></td>
<td>Film evaporation with wall nucleation</td>
<td></td>
</tr>
</tbody>
</table>

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<tbody>
<tr>
<td></td>
<td></td>
<td>Droplet Annular Flow</td>
<td><img src="image" alt="Droplet Annular Flow" /></td>
<td>Vapor core with droplets and liquid film</td>
<td>Steam generator in boiler</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bubbly Droplet Annular Flow</td>
<td><img src="image" alt="Bubbly Droplet Annular Flow" /></td>
<td>Vapor bubbles in liquid film with vapor core</td>
<td>Boiling nuclear reactor channel</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>Melting over a temperature range</td>
<td><img src="image" alt="Melting over a temperature range" /></td>
<td>Solid and mushy zone in liquid</td>
<td>Melting of binary solid</td>
</tr>
<tr>
<td></td>
<td>J</td>
<td>Solidification over a temperature range</td>
<td><img src="image" alt="Solidification over a temperature range" /></td>
<td>Liquid core with layer of solid and mushy zone</td>
<td>Freezing of binary solution</td>
</tr>
</tbody>
</table>
### 1.5 Multiphase Systems and Phase Changes

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<tbody>
<tr>
<td>L</td>
<td>Liquid-vapor bubblly flow</td>
<td>[Image]</td>
<td>Vapor bubbles in a liquid</td>
<td>Chemical reactors</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Liquid-vapor droplet flow</td>
<td>[Image]</td>
<td>Liquid droplets in a vapor</td>
<td>Spray cooling</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Particulate flow</td>
<td>[Image]</td>
<td>(a) Solid particles in liquid (b) Solid particles in gas</td>
<td>(a) melting /solidification of PCM suspension in liquid (b) combustion of solid fuels</td>
<td></td>
</tr>
</tbody>
</table>
1.5.2 Solid-Liquid Phase Change Including Melting and Solidification

- Melting and solidification of pure substances occur at a single temperature, the melting point, which is a property of the substance.
- In a solid-liquid phase change problem, different phases, which possess different thermophysical properties, are separated by an interface.
- Location of the interface is not fixed because the phase change occurring in the substance results in motion of the interface.
- Interfacial velocity is determined by the transient energy balance in the substance, since phase change is always accompanied by the absorption or release of latent heat.
- Successful solution of melting and solidification problems yields the temperature distribution in both the liquid and solid phases as well as the locations of the solid-liquid interfaces.
- The interfacial structure of the solid-liquid phase change occurring at a single temperature can be classified as separated phase because the location of the interface can always be identified.
1.5 Multiphase Systems and Phase Changes

- Since the melting point differs between substances, melting and solidification of multicomponent substances occur over a range of temperatures instead of at a single melting point, as is the case for the single-component substance.
- When the temperature of a multicomponent substance is within the phase-change temperature range, the substance is a mixture of solid and liquid which is termed the *mushy zone*.
- Melting and solidification of multicomponent substances are complicated by the fact that a mushy zone exists between the solid and liquid phases and so there are two moving interfaces:
  - between the solid and mushy zones and
  - between the mushy and liquid zones
- Successful solution of melting and solidification in multicomponent systems yields the temperature and concentration distribution in all three zones as well as the locations of two moving interfaces.
1.5 Multiphase Systems and Phase Changes

1.5.3 Solid-Vapor Phase Change Including Sublimation and Vapor Deposition

- Phase change between solid and liquid occurs when the system pressure is above the triple point pressure.
- When the system pressure is below the triple point pressure, phase change between solid and vapor can occur.
- When heat is applied to the solid with the pressure below the triple point pressure, the vibrational energy of the molecules will be increased and the temperature of the solid will be raised.
- When the temperature of the solid reaches the sublimation temperature, continued heating increases the vibrational energy of the molecules to a level that overcomes the intermolecular attractive force and bonds between molecules can be broken. At this point the solid is vaporized.
The process whereby solid is vaporized without going through the liquid phase is referred to as sublimation.

When a vapor with pressure below the triple point pressure is cooled, decreasing the vapor temperature results in decreasing molecular kinetic energy and decreasing the distance between molecules.

When the vapor reaches a certain temperature, further cooling significantly reduces the intermolecular distance to a level at which the molecules are bonded together and held in a fixed pattern.

The process whereby a vapor phase turns to solid is referred to as deposition, opposite process of sublimation.
There is also a deposition process involving chemical reaction which is referred to as Chemical Vapor Deposition (CVD).

When the gaseous precursors are absorbed by a heated substrate where a chemical reaction takes place the nucleation and lattice incorporation leads to formation of a solid film.

CVD can find applications in coating as well as laser assisted manufacturing processes.
1.5.4 Interfacial Phenomena

Certain phenomena can be observed at the interfacial region between two distinct material regions, which can be demonstrated by considering the following idealized problems shown in Fig. 1.14:

a) Adjacent flow of two immiscible fluids.

b) Two-phase equilibrium of a single substance in a container.

c) Combustion of a liquid droplet in a gas.

d) Chemical reaction between a solid and a gas.
1.5 Multiphase Systems and Phase Changes

Figure 1.14 Examples of interfacial phenomena: (a) Flow of two immiscible fluids between two parallel plates; (b) Pure substance in two phases at equilibrium; (c) Combustion of a liquid fuel droplet in gas; (d) Solid surface reacting with gas in a surrounding atmosphere.
1.5.5 Condensation

From a macroscopic viewpoint, condensation typically occurs when a saturated vapor—pure or multi-component—contacts an object such as a wall or other contaminant that has a temperature below the saturation temperature.

In a multicomponent vapor, the saturation temperature is referred to as the dew point.

In most applications, the cooler object is a solid wall such as those found in the condensers of most industrial applications.

The vapor condenses on the cooled surface as a thin film or as droplets depending on whether the surface is wettable or nonwettable with the condensate [Fig. 1.15(a) and (b)].

As the condensate forms on the cooler wall it becomes subcooled and additional condensate begins to form on the surface of the existing condensate.
1.5 Multiphase Systems and Phase Changes

Figure 1.15 Condensation on a surface: (a) Filmwise condensation, (b) Dropwise condensation.
1.5 Multiphase Systems and Phase Changes

- Film-wise or drop-wise condensation, where the vapor and the heat sink (cold wall) are separated by the condensate, are referred to as indirect contact condensation.

- When a vapor makes contact with a low-temperature liquid that is not attached to the cold wall, condensation occurs on the surface of the low-temperature liquid.

- Since the vapor is in direct contact with the heat sink, the low temperature liquid in this case is referred to as direct contact condensation.

- Direct condensation is limited by the heat capacity of the low temperature liquid. Direct contact condensation includes two cases:
  - vapor condensing on the surface of liquid droplets that are suspended in a gas phase to form a fog,
  - vapor bubbles dispersed throughout the bulk liquid.
1.5.6 Evaporation and Boiling

Figure 1.16 Boiling and evaporation

(a) Evaporation occurring at a liquid-vapor interface

(b) Boiling occurring at a solid-liquid interface

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Evaporation is a liquid-to-vapor transformation process that occurs across a liquid-vapor interface and it is different from boiling that occurs at a solid-liquid (heating) interface (see Fig. 1.16).

Another distinction between evaporation and boiling is that there is no vapor bubbles formed in an evaporation process.

As will be shown in Chapter 8, evaporation can occur from liquid films, drops, and jets.

Films flow on a heated or adiabatic surface as a result of gravity or vapor shear.

Drops may evaporate from a heated substrate, or they may be suspended in a gas mixture or immiscible fluid.

Jets may be cylindrical in shape or elongated (ribbon-like).
Chapter 1: Introduction

1.5 Multiphase Systems and Phase Changes

- Boiling is the liquid-vapor phase change that occurs at a solid-liquid interface when the surface temperature of the solid exceeds the saturation temperature of the liquid.
- This process is characterized by the formation of vapor bubbles, which are initiated at the solid surface and then grow and detach.
- Depending on whether the bulk liquid is quiescent or moving, boiling can be classified as pool boiling or flow boiling, respectively.

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1.5 Multiphase Systems and Phase Changes

- Two-phase flow refers to the interactive flow of two distinct phases with common interfaces in a channel, with each phase representing a mass or volume of matter.
- The two phases can exist as combinations of solid, gas and/or liquid phases.
- Although multiphase flow of three phases can also exist, most multiphase engineering applications are two-phase flow.
- Flow in any channel requires design, development and optimization. It is important to predict the flow phases as well as the flow regimes, which refers to a characteristic flow pattern based on the interfaces formed between the phases.
- This knowledge enables prediction of the pressure drop and heat transfer characteristics based on the flow rate, channel size and operating conditions.
- From the pressure drop data, the proper flow characteristics can be determined to minimize the occurrence of corrosion, erosion, or scale formation, all of which can lead to excessive friction.
Two-phase flow involves fluid flow of a mixture of two phases which can be:

1. liquid-vapor flow
2. liquid-liquid
3. liquid-solid particles
4. gas-solid particles

Two-phase flow involving phase change between the liquid and vapor phases of a single substance is of interest to the heat transfer community and to practicing engineers.

Forced convective condensation and boiling fit into this category.

The fact that each phase in the two-phase flow problem has its own properties, velocity, and temperature makes the solution of two-phase flow and heat transfer problems very challenging.
1.5 Multiphase Systems and Phase Changes

Two-phase flow models can be classified in two types:
1. separated flow models
2. homogeneous flow models

The separated-flow model allows each phase to be assigned a particular region in the flow field where it has its own velocity and temperature.

In order to solve problems involving two-phase flow and phase-change heat transfer, it is necessary to obtain the flow field and temperature distribution of both phases; correct matching conditions at the interfaces between phases must also be applied.

The governing equations for two phases must be given separately and boundary conditions for each phase at the interface must be matched.

However, it is assumed in the homogeneous flow model that the velocities and temperatures of the two phases are identical and therefore the liquid and vapor phases share one set of governing equations.