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Thermodynamics Basics:
*Enthalpy, Entropy, Mollier Diagram
and Steam Tables*

Course No: M08-005
Credit: 8 PDH

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Preface

As the adage goes, “a picture is worth a thousand words;” this text maximizes the utilization of diagram, graphs and flow charts to facilitate quick and effective comprehension of the concepts of thermodynamics by the reader.

This text is designed to serve as a tool for building basic engineering skills in the field of thermodynamics.

If your objective as a reader is limited to the acquisition of basic knowledge in thermodynamics, then the material in this text should suffice. If, however, the reader wishes to progress their knowledge and skills in thermodynamics to intermediate or advance level, this text could serve as a useful stepping stone.

In this text, the study of thermodynamics concepts, principles and analysis techniques is made relatively easy for the reader by inclusion of most of the reference data, in form of excerpts, within the discussion of each case study, exercise and self assessment problem solutions. This is in an effort to facilitate quick study and comprehension of the material without repetitive search for reference data in other parts of the text.

Certain thermodynamic concepts and terms are explained more than once as these concepts appear in different segments of this text; often with a slightly different perspective. This approach is a deliberate attempt to make the study of some of the more abstract thermodynamics topics more fluid; allowing the reader continuity, and precluding the need for pausing and referring to segments where those specific topics were first introduced.

Due to the level of explanation and detail included for most thermodynamics concepts, principles, computational techniques and analyses methods, this text is a tool for those energy engineers, engineers and non-engineers, who are not current on the subject of thermodynamics.

The solutions for end of the segment self assessment problems are explained in just as much detail as the case studies and sample problems in the pertaining segments. This approach has been adopted so that this text can serve as a thermodynamics skill building resource for not just energy engineers but engineers of all disciplines. Since all segments and topics begin with the introduction of important fundamental concepts and principles, this

text can serve as a “brush-up” or review tool for even mechanical engineers whose current area of engineering specialty does not afford them the opportunity to keep their thermodynamics knowledge current.

In an effort to clarify some of the thermodynamic concepts effectively for energy engineers whose engineering education focus does not include thermodynamics, analogies are drawn from non-mechanical engineering realms, on certain complex topics, to facilitate comprehension of the relatively abstract thermodynamic concepts and principles.

Each segment in this text concludes with a list of questions or problems, for self-assessment, skill building and knowledge affirmation purposes. The reader is encouraged to attempt these problems and questions. The answers and solutions, for the questions and problems, are included under Appendix A of this text.

For reference and computational purposes, steam tables and Mollier (Enthalpy-Entropy) diagrams are included in Appendix B.

Most engineers understand the role units play in definition and verification of the engineering concepts, principles, equations and analytical techniques. Therefore, most thermodynamic concepts, principles and computational procedures covered in this text are punctuated with proper units. In addition, for the reader’s convenience, units for commonly used thermodynamic entities, and some conversion factors are listed under Appendix C.

Most thermodynamic concepts, principles, tables, graphs, and computational procedures covered in this text are premised on US/Imperial Units as well as SI/Metric Units. Certain numerical examples, case studies or self-assessment problems in this text are premised on *either* the SI unit realm *or* the US unit system. When the problems or numerical analysis are based on only one of the two unit systems, the given data and the final results can be transformed into the desired unit system through the use of unit conversion factors in Appendix C.

Some of the Greek symbols, used in the realm of thermodynamics, are listed in Appendix D, for reference.

What readers can gain from this text:

- Better understanding of thermodynamics terms, concepts, principles, laws, analysis methods, solution strategies and computational techniques.
- Greater confidence in interactions with thermodynamics design engineers and thermodynamics experts.
- Skills and preparation necessary for succeeding in thermodynamics portion of various certification and licensure exams, i.e. CEM, FE, PE, and many other trade certification tests.
- A better understanding of the thermodynamics component of heat related energy projects.
- A compact and simplified thermodynamics desk reference.

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Segment 1

Study of Enthalpy and Entropy

Topics

- Enthalpy
- Entropy

Introduction

Similar to the last segment, the goal in this brief segment is to continue the introduction of basic, yet critical, concepts in the field of thermodynamics. In this segment, we will introduce the concept of *entropy* and we will expand on the concept of *enthalpy*. As we progress through this text, you will notice that the discussion on entropy will be limited, reflecting the somewhat limited role of entropy in practical thermodynamics. On the other hand, our continued exploration of enthalpy, in this segment, and the ones heretofore, is indicative of the instrumental and ubiquitous role of enthalpy in the study of thermodynamics. We received a brief, preliminary, introduction to enthalpy in the last segment, in the context of energy flow in power generating realm. In this segment, we will expand on enthalpy in preparation for its examination in more complex thermodynamic scenarios.

Enthalpy: Enthalpy is defined as the total heat content or total useful energy of a substance. The symbol for enthalpy is “**h**.” Enthalpy is also considered to be the sum of internal energy “**u**” and flow energy (or flow work) **p.V**. This definition of enthalpy can be expressed, mathematically, as follows:

$$\mathbf{h = u + p.V} \qquad \mathbf{Eq. 1.1}$$

Where,

h = Specific enthalpy, measured in **kJ/kg** (SI Units) or **BTU/lbm** (US Units)

u = Specific internal energy, measured in **kJ/kg** (SI Units) or **BTU/lbm** (US Units)

p = Absolute Pressure measured in **Pa** (SI Units), or **psf** (US Units)

V = Volume measured in **m³** (SI Units), or **ft³** (US Units)

p.V = Flow Energy, Flow Work or p-V work, quantified in **kJ/kg** (SI Units) or **BTU/lbm** (US Units)

In practical saturated or superheated steam systems, internal energy, **u**, specific enthalpy, **h**, and specific volume, **v**, can be assessed through saturated steam tables and superheated steam tables, respectively. The terms saturated steam and superheated steam are defined in depth later in this text. Segments 5 and 6 cover classifications of steam and associated steam tables in detail. Reference steam tables, in US and SI form, are included in Appendix B of this text.

In order to maintain consistency of units in practical thermodynamic situations, where computation is performed in **US units**, a more suitable form of the enthalpy equation **Eq. 1.1** would be as follows:

$$h = u + p.V/J \quad \text{Eq. 1.2}$$

Where,

h = Enthalpy, measured in **BTU's**

u = Internal energy, measured in **BTU**

p = Absolute Pressure measured in **psf** or **lbf/ft²**

V = Volume measured in **ft³**

J = Joule's constant; value of **J** is **778 ft-lbf/BTU**

Note that in the SI unit system, an alternate version of enthalpy equation Eq. 1.1 is not necessary because units in Eq. 1.1 are congruent.

Enthalpy can also be quantified in molar form. In molar form, enthalpy is referred to as **molar enthalpy** and represented by the symbol "**H**".

The units for molar enthalpy **H** are **BTU/lbmole** in the US system, and **kJ/kmole** in the Metric or SI System; where a mole of a substance is defined or calculated through division of the mass of that substance by the atomic weight of the substance, if it is a solid, or by the molecular weight, if it is a liquid or gas.

The mathematical equation for **molar enthalpy "H,"** is as follows:

$$H = U + p.V \quad \text{Eq. 1.3}$$

Where,

U = **Molar Internal Energy**, can be expressed in **BTU/lbmol** (US Units) or **kJ/kmol** (SI Units)

p = Absolute pressure measured in **Pa** (SI Units), **psf** (US Units) or **lbf/ft²**

V = Molar specific volume measured in **m³/kmol** (SI Units), or **ft³/lbmole** (US Units)

Example 1.1

Calculate the absolute enthalpy, **h**, in **BTU's**, for **1 lbm of vapor** under the following conditions:

h = Enthalpy, measured in **BTU's** =?

u = **1079.9 BTU/lbm**

p = **14.14 psia**

V = **27.796 ft³**

J = Joule's constant; value of **J** is **778 ft-lbf/BTU**

Solution:

The pressure is given in psia, or **lbf/in²**. In order to streamline the pressure for application in **Eq. 1.2**, we must convert it into **lbf/ft²**.

Therefore,

$$\begin{aligned} p &= (14.14 \text{ lbf/in}^2) \cdot (144 \text{ in}^2/\text{ft}^2) \\ &= 2,036 \text{ lbf/ft}^2 \end{aligned}$$

Then, by applying **Eq. 1.2**, and by substitution of known and derived values:

$$h = u + p \cdot V/J$$

$$h = 1079.9 \text{ BTU/lbm} + (2,036 \text{ lbf/ft}^2) \cdot (27.796 \text{ ft}^3) / 778 \text{ ft-lbf/BTU}$$

$$h = 1152.67 \text{ BTU}$$

Entropy

Entropy is defined as the non-work producing form of energy. It is also regarded as the energy that is not available for performing useful work within a certain environment. The symbol for entropy is “s.” Some facts, principles and laws associated with entropy are summarized below:

- Increase in entropy is referred to as entropy production.
- The total absolute entropy of a system is said to be equal to the sum of all absolute entropies that have occurred over the life of the system.

$$S_{\text{total}} = \sum \Delta s_i \quad \text{Eq. 1.4}$$

Where, Δs_i represents change in enthalpy at each object or in each substance. Application of this entropy principle will be demonstrated through Case Study 1.1.

- According to the **third law of thermodynamics**, the absolute entropy of a perfect crystalline solid, in thermodynamic equilibrium, approaches zero as the temperature approaches absolute zero.

$$T \xrightarrow{\text{Limit}} 0^\circ K \quad s = 0$$

- In an *isothermal* (constant temperature) process, the entropy production, Δs , is a function of the energy transfer rate:

$$\Delta s = q / T_{\text{abs}} \quad \text{Eq. 1.5}$$

Where,

s = entropy in **kJ/kg.°K** (SI Units System), or in **BTU/lbm.°R** (US Unit System)

q = Heat transferred in **kJ/kg**, (SI Units) or **BTU/lbm** (US Units)

T_{abs} = Absolute Temperature of the object or substance, in **°K** (SI Units System), or in **°R** (US Unit System)

Case Study 1.1 - Entropy Analysis

In a certain solar system there are four (4) planets oriented in space as shown in Figure #2. Their temperatures are indicated in the diagram, in °K as well as in °R. As apparent from the orientation of these planets in Figure 1.1, they are exposed to each other such that heat transfer can occur freely through radiation. All four (4) planets are assumed to be massive enough to allow for the interplanetary heat transfer to be isothermal for each of the planets.

- Will heat transfer occur, through radiation, from planet Z to planets X and Y?
- If the 3,000 kJ/kg of radiated heat transfer occurs from planet X to planet Y, what would be the entropy changes at each of the two planets?
- Can convectional heat transfer occur between any of two planets in this solar system?
- If certain radiated heat transfer between Planets Y and Z causes an entropy change of **11.77 kJ/kg.°K** at Planet Y and an entropy change of **12.66 kJ/kg.°K** at Planet Z, what would be the overall, resultant, entropy of this planetary system?
- Can planet X be restored to its original state? If so, how?

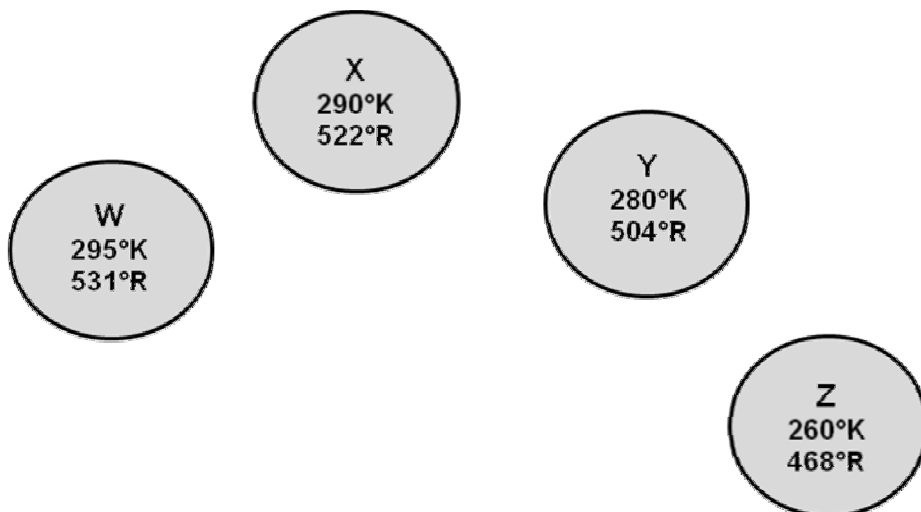


Figure 1.1 – Case Study 1.1, Entropy

Solution - Case Study 1.1:

a) Will heat transfer occur, through radiation, from planet Z to planets X and Y?

Solution/Answer:

Heat flows *from a body at a higher temperature to one that is at a lower temperature*. The temperature of Planet Z is lower than the temperature of planets X and Y. Therefore, **NO radiated heat transfer will occur from planet Z to planets X and Y.**

b) If the **3000 kJ /kg** of radiated heat transfer occurs from planet X to planet Y, what would be the entropy changes at each of the two planets?

Solution/Answer:

In an *isothermal* (constant temperature) process, the entropy production, Δs , is a function of the energy transfer rate and its relationship with heat q and absolute temperature, T_{abs} and is represented by **Eq. 1.5**:

$$\Delta s = q / T_{abs}$$

$$\therefore \Delta s_X = (- 3,000 \text{ kJ/kg}) / (290^\circ\text{K})$$

$$= - 10.34 \text{ kJ/kg.}^\circ\text{K} \text{ \{Due to heat loss by Planet X\}}$$

And,

$$\Delta s_Y = (+3,000 \text{ kJ/kg}) / (280^\circ\text{K})$$

$$= + 10.71 \text{ kJ/kg.}^\circ\text{K} \text{ \{Due to heat gain by Planet Y\}}$$

c) Can convectonal heat transfer occur between any of two planets in this solar system?

Solution/Answer:

Convectonal heat transfer is dependent on bulk movement of a fluid (gaseous or liquid) and, therefore, it can *only* occur in liquids, gases and multiphase mixtures. Since, the system in this problem is a planetary system, the medium between the bodies is devoid of fluids needed for convectonal heat transfer. Heat transfer in this planetary system occurs through radiation, primarily.

Therefore, the answer is NO.

d) If the heat transfer from part (b) occurs simultaneous to a certain radiated heat transfer between Planets Y and Z, where the entropy change of - 11.77 kJ/kg. °K is recorded at Planet Y and an entropy change of 12.66 kJ/kg.°K is recorded at Planet Z, what would be the overall, resultant, entropy of this planetary system?

Solution/Answer:

$$\text{Overall } \Delta S_{\text{Planetary System}} = \sum (\Delta S_i)$$

$$\therefore \text{Overall } \Delta S_{\text{Planetary System}} = \Delta S_X + \Delta S_Y + \Delta S_{YZ} + \Delta S_Z$$

Or,

$$\Delta S_{\text{Planetary System}} = -10.34 \text{ kJ/kg.}^\circ\text{K} + 10.71 \text{ kJ/kg.}^\circ\text{K} - 11.77 \text{ kJ/kg.}^\circ\text{K} + 12.66 \text{ kJ/kg.}^\circ\text{K}$$

$$\therefore \text{Overall } \Delta S_{\text{Planetary System}} = + 1.2643 \text{ kJ/kg.}^\circ\text{K}$$

e) Can planet X be restored to its original state? If so, how?

Solution/Answer:

Planet X *can* be restored to its original state; through absorption of **3,000 kJ/kg of (specific) heat energy.**

Segment 1

Self Assessment Problems & Questions

1. Calculate the volume **1 kg** of vapor would occupy under the following conditions:

$$\begin{aligned}h &= 2734 \text{ kJ} \\u &= 2550 \text{ kJ} \\p &= 365.64 \text{ kPa} = 365.64 \text{ kN/m}^2 \\V &= ?\end{aligned}$$

2. In a certain solar system there are four (4) planets oriented in space as shown in Figure 1.1. As apparent from the orientation of these planets, they are exposed to each other such that heat transfer can occur freely through radiation. All four (4) planets are assumed to be massive enough to allow for the interplanetary heat transfer to be an isothermal phenomenon for each of the planets. *Perform all computation in the US Unit System.*

- a. If the **1,300 BTU/lbm** of radiated heat transfer occurs from **planet X to planet Y**, what would be the entropy changes at each of the two planets?
- b. If a certain radiated heat transfer between Planets Y and Z causes an entropy change of **-2.9 BTU/lbm.°R** at Planet **Y** and an entropy change of **3.1 BTU/lbm.°R** at Planet **Z**, what would be the overall, resultant, entropy of this planetary system?
- c. If the mass of vapor under consideration in problem 1 were tripled to 3 kg, what would be the impact of such a change on the volume?
- d. Would **Eq. 1.2** be suitable for calculation of enthalpy if all available data is in **SI (Metric) units**?

Segment 2

Understanding Mollier Diagram

Topic:

- Mollier diagram and its applications.

Introduction

Mollier diagram is named after Richard Mollier (1863-1935), a German professor who pioneered experimental research on thermodynamics associated with water, steam and water-vapor mixture. Mollier diagram is a graphical representation of a functional relationship between enthalpy, entropy, temperature, pressure and quality of steam. Mollier is often referred to as **Enthalpy – Entropy Diagram** or **Enthalpy – Entropy Chart**. The enthalpy-entropy charts in Appendix B are Mollier Diagrams. They used commonly in the design and analysis associated with power plants, steam turbines, compressors, and refrigeration systems.

Mollier diagram is available in two basic versions: The SI/Metric Unit version and the US/Imperial Unit version. **Figure 2.1** depicts the SI/Metric version of the Mollier diagram. The US and SI versions of the Mollier diagram are included in Appendix B. The abscissa (horizontal or x-axis in a Cartesian coordinate system) and ordinate (vertical or y-axis in a Cartesian coordinate system) scales represent **entropy** and **enthalpy**, respectively. Therefore, Mollier diagram is also referred to as the **Enthalpy-Entropy Chart**.

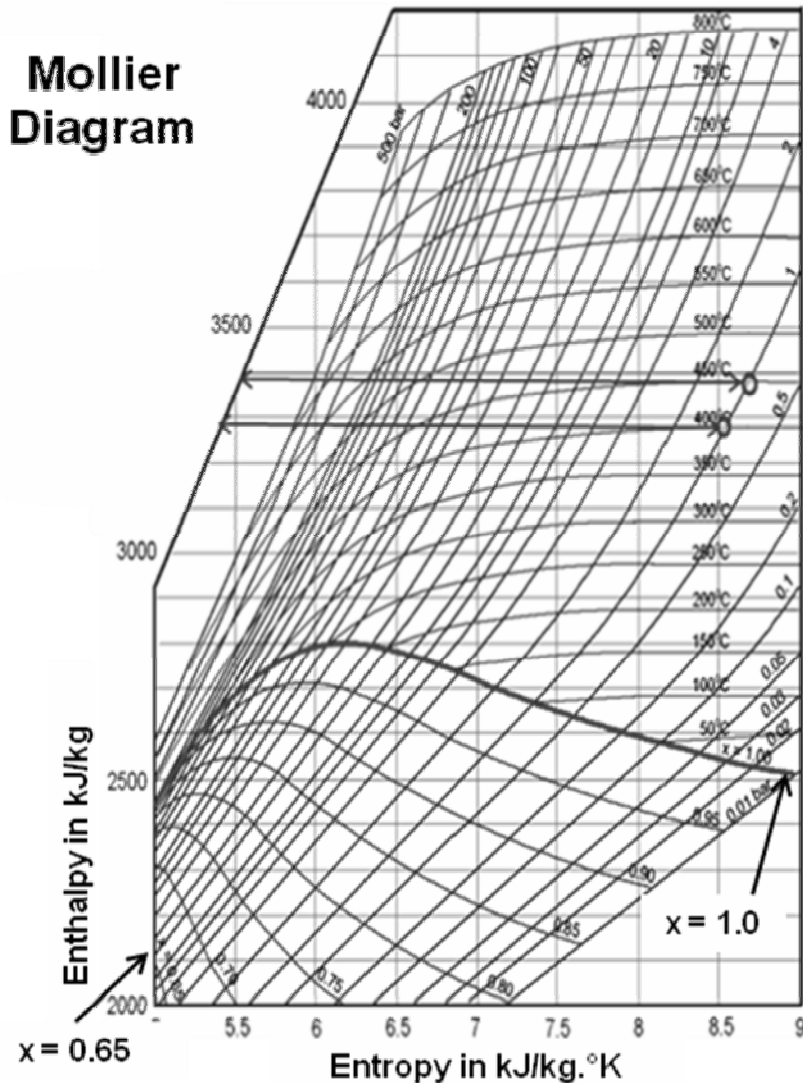


Figure 2.1 – Mollier Diagram, SI/Metric Units

The constant pressure and constant temperature lines in the Mollier diagram are referred to as isobars and isotherms, respectively. In addition, the graph includes lines representing constant steam quality, “x,” in the bottom half of the diagram. The bold line, spanning from left to right, in the lower half of Mollier diagram is the **saturation line**. The saturation line, labeled as **x = 1**, represents the set of points on Mollier diagram where the steam is 100% vapor. All points above the saturation line are in the **superheated steam realm**. All points below the saturation line represent a **mixture of liquid and**

vapor phases. The concept of quality is explained and illustrated in Segment 3.

A comparison of the Mollier diagram and the psychrometric chart reveals convincing similarity between these two versatile and commonly applied thermodynamics tools. Some schools of thought explain the process of transformation of the Mollier diagram to the psychrometric chart on the basis of geometric manipulation. This relationship between Mollier diagram and the psychrometric chart is apparent from the fact that both involve critical thermodynamic properties such as **enthalpy, temperature, sensible heat, latent heat and quality.**

A comparison of the **Mollier diagram** and the **steam tables** also reveals a marked similarity and equivalence between the two. This equivalence is illustrated through **Example 3.6** in Segment 3. The reader would be better prepared to appreciate the illustration of the relationship between the Mollier diagram and the steam tables after gaining a clear comprehension of the saturated and superheated steam tables in Segment 3. Example 3.6 demonstrates the interchangeability of the Mollier diagram and the **Superheated Steam Tables** as equivalent tools in deriving the enthalpy values associated with the change in the temperature of superheated steam. This equivalence between Mollier diagram and the steam tables is further reinforced by the fact that *both* involve critical thermodynamic properties of steam such as **enthalpy, entropy, temperature and pressure.**

Application of Mollier Diagram

A common application of Mollier diagram involves determination of an unknown parameter among the key Mollier diagram parameters such as, ***enthalpy, entropy, temperature pressure and quality.*** Typical applications of Mollier diagram are illustrated through the example problems that follow.

Example 2.1

Determine if steam at 450°C and 1 bar is saturated or superheated. Find the enthalpy and entropy of this steam.

Solution:

See the Mollier diagram in **Figure 2.2.** Identify the point of intersection of the 450°C line (or 450°C isotherm) and the constant pressure line (or isobar) of 1

bar. This point of intersection of the two lines is labeled **A**. As explained above, this region of the Mollier diagram is the superheated steam region.

Therefore, the steam at 450°C and 1 bar is superheated.

Enthalpy Determination: To determine the enthalpy at point **A**, draw a straight horizontal line from point **A** to the left till it intersects with the diagonal enthalpy line. This horizontal line intersects the enthalpy line at an enthalpy value of, approximately, 3380 kJ/kg.

Therefore, h_A , or enthalpy at point A, is 3380 kJ/kg.

Entropy Determination: To determine the entropy at point **A**, draw a straight vertical line from point **A** to the bottom, until it intersects with the entropy line. The vertical line intersects the entropy line at, approximately, 8.7kJ/kg.°K.

Therefore, s_A , or entropy at point A, is 8.7kJ/kg.°K.

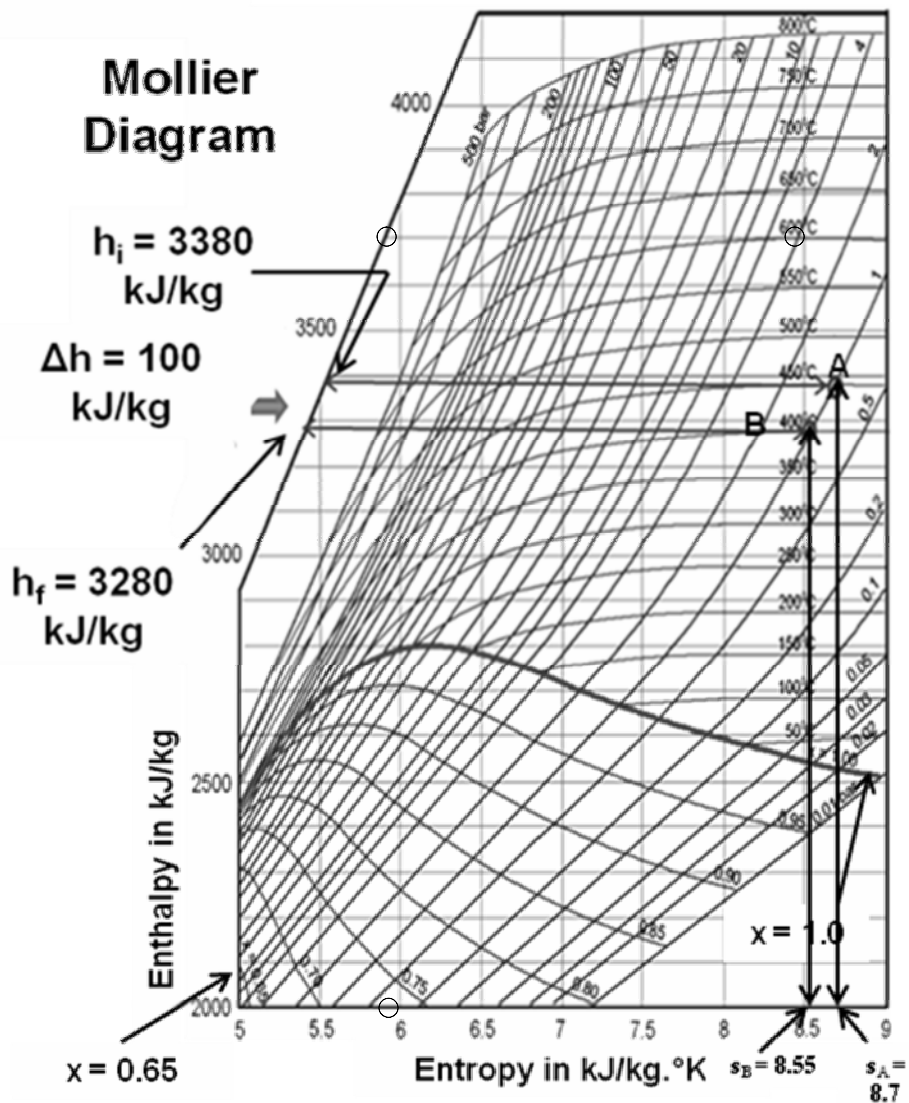


Figure 2.2 – Mollier Diagram, SI/Metric Units

Example 2.2

Determine the amount of heat that must be removed from a system, on per kg basis, in order to reduce the temperature of steam from **450°C, at 1 Atm.** to **400°C, at 1 Atm.**

Solution:

To determine the amount of heat that must be removed from the steam in order to cool the steam from **450°C**, at **1 Atm.** to **400°C**, at **1 Atm**, we must assess the enthalpies at those two points.

The first point, at **450°C and 1 Atm**, was labeled as point **A** in Example 2.1. The enthalpy, **h_i** at point A was determined to be **3380 kJ/kg**.

The enthalpy, **h_f**, at the second point, referred to as point **B**, as shown on the Mollier diagram in Figure 2.2, is **3280 kJ/kg**.

Therefore, the amount of heat that must be removed from the system in order to lower the temperature from **450°C to 400°C**, at **1 Atm**, would be:

$$\Delta h = h_i - h_f$$

$$\therefore \Delta h = h_i - h_f = 3380 \text{ kJ/kg} - 3280 \text{ kJ/kg} = 100 \text{ kJ/kg}$$

In other words, **100 kJ of heat must be removed from each kg of steam** in order to cool it from **450°C**, at **1 Atm.** to **400°C**, at **1 Atm.**

Segment 2

Self Assessment Problems & Questions

1. Using the Mollier diagram, find the entropy of steam at 400°C and 1 Atm.
2. Heat is removed from a thermodynamic system such that the temperature drops from **450°C**, at **1 Atm** to **150°C**, at **1 Atm**. Determine the following:
 - a) The new, or final, Enthalpy
 - b) The new entropy
 - c) The state of steam at **150°C** and **1 Atm**

Segment 3

Saturated and Superheated Steam Tables

Topics:

- Saturated Steam Tables
- Superheated Steam Tables.

Introduction

In this segment, as we study various topics of thermodynamics, we will utilize and focus on two main categories of steam tables: (1) The Saturated Steam Tables and (2) The Superheated Steam Tables.

Appendix B of this text includes the compact version of the saturated steam tables and the superheated steam tables. These tables are referred to as the compact version because they do not include certain properties or attributes that are customarily included only in the detailed or comprehensive version. Characteristics or properties included in most comprehensive version of the saturated steam tables, but omitted in Appendix B steam tables, are as follows:

- 1) Internal energy “U.”
- 2) The heat of vaporization “ h_{fg} .”

Internal energy, absolute and specific, is not required in most common thermodynamic analysis. And, heat of vaporization, h_{fg} for water, as explained in Segment 6, is a derivative entity. In that, h_{fg} can be derived from h_L and h_V as stipulated by **Eq. 3.1** below:

$$h_{fg} = h_V - h_L \quad \text{Eq. 3.1}$$

Example 3.1:

Using the saturated liquid enthalpy value for h_L and the saturated vapor enthalpy value for h_V , at 1 MPa and 180°C, as listed in the saturated steam table excerpt in **Table 3.1**, verify that $h_{fg} = 2015 \text{ kJ/kg}$.

Solution:

As stated in **Eq. 3.1**:

$$h_{fg} = h_v - h_L$$

As read from **Table 3.1**:

$$h_v = 2777 \text{ kJ/kg, and}$$

$$h_L = 762.68 \text{ kJ/kg}$$

$$\begin{aligned} \therefore h_{fg} &= h_v - h_L \\ &= 2777 - 762.68 \\ &= 2014.32 \text{ kJ/kg} \end{aligned}$$

The value for h_{fg} , at 1.0 MPa and 180°C, as listed in **Table 3.1**, is **2015 kJ/kg**, versus the derived value of **2014 kJ/kg**. The difference between the calculated value of h_{fg} , at 1.0 MPa and 180°C and the value listed in **Table 3.1** is only 0.05% and is, therefore, negligible. Hence, we can say that **Eq. 3.1** stands verified as a tool or method for deriving the heat of vaporization h_{fg} from the compact version of steam tables included in Appendix B.

Properties of Saturated Steam By Pressure									
Metric/SI Units									
Abs. Press. MPa	Temp. °C	Specific Volume m ³ /kg		Enthalpy kJ/kg			Entropy kJ/kg		Abs. Press. MPa
		Sat. Liquid v_L	Sat. Vapor v_W	Sat. Liquid h_L	Evap. h_{fg}	Sat. Vapor h_V	Sat. Liquid s_L	Sat. Vapor s_V	
0.010	45.81	0.0010103	14.671	191.81	2392.8	2583.9	0.6492	8.1489	0.010
0.10	99.61	0.0010431	1.6940	417.44	2258.0	2674.9	1.3026	7.3588	0.10
0.20	120.21	0.0010605	0.88574	504.68	2201.9	2706.2	1.5301	7.1269	0.20
1.00	179.89	0.0011272	0.19435	762.68	2015.3	2777.1	2.1384	6.5850	1.00

Table 3.1 – Properties of Saturated Steam, by Pressure, SI Units

The saturated and superheated steam tables in Appendix B are presented in the US/Imperial unit realm as well as the SI/Metric realm. Note that in this segment, as well as other segments in this text, for the readers' convenience, saturated steam table excerpts include the heat of vaporization, h_{fg} , values. See **Tables 3.1, 3.3, 3.4, and 3.5**.

Also, for illustration of various numerical examples and thermodynamics discussion in general, excerpts from the superheated steam tables in Appendix , are included in this segment in the form of **Tables 3.2, 3.6 and 3.7**.

Saturated Steam Tables

Saturated water and steam tables, as presented in Appendix B, are categorized as follows:

- A. Saturated water and steam tables, by temperature, in US Units
- B. Saturated water and steam tables, by pressure, in US Units
- C. Saturated water and steam tables, by temperature, in SI/Metric Units
- D. Saturated water and steam tables, by pressure, in SI/Metric Units

A. Saturated water and steam tables, by temperature, in US Units: As apparent from the inspection of the four categories of saturated steam tables above, two distinguishing factors between these categories of tables are temperature and pressure. First category of tables, listed under bullet A, represents saturated water and steam data by *temperature*, in US Units. In other words, this set of tables is used when temperature is the determining factor, or when the current or future state of the saturated water or saturated steam is premised on or defined by the temperature. So, if saturated water or saturated steam is said to exist at a given temperature, the following properties can be identified:

- a) **Saturation pressure**, in psia, at the given temperature, in °F.
- b) **Specific volume**, v_L , in ft^3/lbm , of saturated liquid, at the given temperature and saturation pressure.

- c) **Specific volume, v_v** , in ft^3/lbm , of saturated vapor, at the given temperature and saturation pressure.
- d) **Specific enthalpy, h_L** , in BTU/lbm , of saturated liquid, at the given temperature and saturation pressure.
- e) **Specific enthalpy, h_v** , in BTU/lbm , of saturated vapor, at the given temperature and saturation pressure.
- f) **Specific entropy, s_L** , in $\text{BTU}/\text{lbm}\text{-}^\circ\text{R}$, of saturated liquid, at the given temperature and saturation pressure.
- g) **Specific entropy, s_v** , in $\text{BTU}/\text{lbm}\text{-}^\circ\text{R}$, of saturated vapor, at the given temperature and saturation pressure.

B. Saturated water and steam tables, by pressure, in US Units: The second category of tables represents saturated water and steam data by **pressure**, in US Units. In other words, this set of tables is used when pressure is the determining factor, or when the current or future state of the saturated water or saturated steam is defined by the pressure. So, if saturated water or saturated steam is said to exist at a given pressure, the following properties can be identified:

- a) **Saturation temperature**, in $^\circ\text{F}$, at the given pressure, in $\text{psia } ^\circ\text{F}$.
- b) **Specific volume, v_L** , in ft^3/lbm , of saturated liquid, at the given pressure and saturation temperature.
- c) **Specific volume, v_v** , in ft^3/lbm , of saturated vapor, at the given pressure and saturation temperature.
- d) **Specific enthalpy, h_L** , in BTU/lbm , of saturated liquid, at the given pressure and saturation temperature.
- e) **Specific enthalpy, h_v** , in BTU/lbm , of saturated vapor, at the given pressure and saturation temperature.

- f) **Specific entropy, s_L** , in BTU/lbm-°R, of saturated liquid, at the given pressure and saturation temperature.
- g) **Specific entropy, s_v** , in BTU/lbm-°R, of saturated vapor, at the given pressure and saturation temperature.

C & D: Saturated steam tables categorized as C and D above are very similar to categories A and B, with the exception of the fact that the temperature, pressure, specific volume, enthalpy and entropy are in the **metric unit system**.

Superheated Steam Tables

Superheated steam tables, as presented in Appendix B, are categorized as follows:

- A. Superheated steam tables in US Units
- B. Superheated steam tables in SI/Metric Units

Unlike the saturated steam tables, regardless of the unit system, the superheated steam tables differ from the saturated steam tables as follows:

- a) Superheated steam tables, such as the ones included under Appendix B, provide only the **specific volume, enthalpy and entropy**, for a given set of temperature and pressure conditions.
- b) Retrieval of specific values of enthalpy and entropy from the superheated steam tables requires knowledge of the exact temperature and pressure.
- c) When the exact temperature and pressure for a given superheated steam condition are not available or listed in the superheated steam tables, **single or double interpolation** is required to identify the specific volume, enthalpy and entropy.

Single and Double Interpolation of Steam Table Data:

Interpolation is often required when retrieving data from tables such as the Saturated Steam Tables or the Superheated Steam Tables. Interpolation is needed when the given pressure or temperature don't coincide with the standard pressure and temperature values on the given tables.

Example 3.2 offers an opportunity to study the interpolation method in the US unit realm. Even though the interpolation method is being illustrated on the basis of steam tables in this segment, this technique can be employed for interpolation of other types of tabular data as well.

Example 3.2:

Calculate the enthalpy of 450 psia and 950°F superheated steam.

Solution:

As you examine the superheated steam tables for these parameters, in Appendix B, you realize that the exact match for this data is not available in the table. See **Tables 3.2 and 3.3**, below, for excerpts from the superheated steam tables in Appendix B.

While the given pressure of 450 psia is listed, the stated temperature of 950°F is not listed. Therefore, the enthalpy for 450 psia and 950°F superheated steam and must be derived by applying interpolation to the enthalpy data listed in the tables for 900°F and 1,000°F.

The formula for *single interpolation*, applied between the stated or available enthalpy values for 900°F and 1000°F, at 450 psia, is as follows:

$$\begin{aligned} h_{950^\circ\text{F}, 450 \text{ psia}} &= ((h_{1000^\circ\text{F}, 450 \text{ psia}} - h_{900^\circ\text{F}, 450 \text{ psia}}) / (1000^\circ\text{F} - 900^\circ\text{F})) \cdot (950 - 900) \\ &\quad + h_{900^\circ\text{F}, 450 \text{ psia}} \end{aligned}$$

Substituting enthalpy values and other given data from the superheated steam table excerpt, shown in **Table 3.2**, yields:

$$h_{950\text{ }^\circ\text{F}, 450\text{ psia}} = ((1522.4\text{ BTU/lbm} - 1468.6\text{ BTU/lbm}) / (1000^\circ\text{F} - 900^\circ\text{F})) \cdot (950 - 900) + 1468.6\text{ BTU/lbm} = 1496\text{ BTU/lbm}$$

Note: The available enthalpy values are circled in **Table 3.2**.

Properties of Superheated Steam						
US/Imperial Units						
Abs. Press. psia	Temp. °F	Note: v is in ft^3/lbm , h is in BTU/lbm and s is in $\text{BTU}/(\text{lbm}\cdot^\circ\text{R})$				
		(Sat. Temp. °F)	500	700	900	1000
260 (404.45)	v		2.062	2.5818	3.0683	3.3065
	h		1262.5	1370.8	1475.2	1527.8
	s		1.5901	1.6928	1.7758	1.8132
360 (434.43)	v		1.446	1.8429	2.2028	2.3774
	h		1250.6	1365.2	1471.7	1525
	s		1.5446	1.6533	1.7381	1.7758
450 (456.32)	v		1.1232	1.4584	1.7526	1.8942
	h		1238.9	1360	1468.6	1522.4
	s		1.5103	1.6253	1.7117	1.7499
600 (486.25)	v				1.3023	1.411
	h				1463.2	1518
	s				1.577	1.7159

Table 3.2, Superheated Steam Table Excerpt, US/Imperial Units

Example 3.3 offers an opportunity to study the **double interpolation method**. As is the case with the single interpolation method, even though the double interpolation method is being illustrated on the basis of steam tables in this segment, this technique can be employed for *double interpolation* of other types of tabular data as well.

Example 3.3:

Calculate the enthalpy of 405 psia and 950°F superheated steam.

Solution:

As you examine the superheated steam tables for these parameters in Appendix B, you realize that the exact match for this data is not available. See **Table 3.2** for an excerpt of the superheated steam tables in Appendix B.

In this example, neither the given pressure of 405 psia nor the stated temperature of 950°F is listed in Appendix B superheated steam tables. Therefore, the enthalpy for 405 psia and 950°F superheated steam and must be derived by applying double interpolation to the enthalpy data listed in Table 3.2 for 360 psia¹, 450 psia, 900°F and 1,000°F.

¹**Note:** Since the enthalpy data for 400 psia is available in Appendix B, double interpolation could be performed on 400 psia and 450 psia points *yielding the same results*. The lower pressure point of 360 psia is chosen in this example simply to maintain continuity with the superheated steam table excerpt in **Table 3.2**.

The double interpolation approach, as applied here, will entail three steps:

The first step involves determination of $h_{900\text{ }^\circ\text{F}, 405\text{ psia}}$, the enthalpy value at 405 psia and 900°F. The enthalpy values available and used in this first interpolation step are circled in Table 3.2. The following formula sums up the mathematical approach to this first step:

$$h_{900\text{ }^\circ\text{F}, 405\text{ psia}} = ((h_{900\text{ }^\circ\text{F}, 360\text{ psia}} - h_{900\text{ }^\circ\text{F}, 450\text{ psia}}) / (450\text{ psia} - 360\text{ psia})) \cdot (450\text{ psia} - 405\text{ psia}) + h_{900\text{ }^\circ\text{F}, 450\text{ psia}}$$

Substituting enthalpy values and other given data from the superheated steam table excerpt, shown in **Table 3.2**, yields:

$$\begin{aligned}h_{900\text{ }^{\circ}\text{F}, 405\text{ psia}} &= ((1471.7\text{ BTU/lbm} - 1468.6\text{ BTU/lbm})/(450\text{ psia} - 360\text{ psia})).(450\text{ psia} - 405\text{ psia}) + 1468.6\text{ BTU/lbm} \\ &= 1470\text{ BTU/lbm}\end{aligned}$$

The second interpolation step involves determination of $h_{1000\text{ }^{\circ}\text{F}, 405\text{ psia}}$, the enthalpy value at 405 psia and 1000°F. The enthalpy values available and used in this interpolation step are circled in Table 3.2. The following formula sums up the mathematical approach associated with this interpolation step:

$$\begin{aligned}h_{1000\text{ }^{\circ}\text{F}, 405\text{ psia}} &= ((h_{1000\text{ }^{\circ}\text{F}, 360\text{ psia}} - h_{1000\text{ }^{\circ}\text{F}, 450\text{ psia}})/(450\text{ psia} - 360\text{ psia})).(450\text{ psia} - 405\text{ psia}) + h_{1000\text{ }^{\circ}\text{F}, 450\text{ psia}}\end{aligned}$$

Substituting enthalpy values and other given data from the superheated steam table excerpt, shown in **Table 3.2**, yields:

$$\begin{aligned}h_{1000\text{ }^{\circ}\text{F}, 405\text{ psia}} &= ((1525\text{ BTU/lbm} - 1522.4\text{ BTU/lbm})/(450\text{ psia} - 360\text{ psia})).(450\text{ psia} - 405\text{ psia}) + 1522.4\text{ BTU/lbm} \\ &= 1524\text{ BTU/lbm}\end{aligned}$$

The final step in the double interpolation process, as applied in this case, involves interpolating between $h_{1000\text{ }^{\circ}\text{F}, 405\text{ psia}}$ and $h_{900\text{ }^{\circ}\text{F}, 405\text{ psia}}$, the enthalpy values derived in the first two steps above, to obtain the desired final enthalpy

$h_{950\text{ }^{\circ}\text{F}, 405\text{ psia}}$.

The formula for this final step is as follows:

$$\begin{aligned}h_{950\text{ }^{\circ}\text{F}, 405\text{ psia}} &= ((h_{1000\text{ }^{\circ}\text{F}, 405\text{ psia}} - h_{900\text{ }^{\circ}\text{F}, 405\text{ psia}})/(1000\text{ }^{\circ}\text{F} - 900\text{ }^{\circ}\text{F})).(950\text{ }^{\circ}\text{F} - 900\text{ }^{\circ}\text{F}) \\ &\quad + h_{900\text{ }^{\circ}\text{F}, 405\text{ psia}}\end{aligned}$$

Substituting enthalpy values derived in the first two steps above, yields:

$$\begin{aligned}h_{950^\circ\text{F}, 405 \text{ psia}} &= ((1524 \text{ BTU/lbm} - 1470 \text{ BTU/lbm}) / (1000^\circ\text{F} - 900^\circ\text{F})) \cdot (950^\circ\text{F} - 900^\circ\text{F}) \\ &\quad + 1470 \text{ BTU/lbm} \\ &= 1497 \text{ BTU/lbm}\end{aligned}$$

Example 3.4:

Determine the enthalpy of saturated water at 20°C and 1 Bar.

Solution:

The saturation temperature at 1 Bar, 1 Atm, or 101 kPa, as stated in the saturated steam tables in Appendix B, is 99.6°C or, approximately, 100°C. The saturated water in this problem is at 20°C; which is well below the saturation temperature. Therefore, the water is in a subcooled state.

In the subcooled state, saturated water's enthalpy is determined by its temperature and not the pressure. Hence, the enthalpy of saturated water at 20°C must be retrieved from the temperature-based saturated steam tables.

From Appendix B, and as circled in Table 3.3, the enthalpy of saturated water at 20°C is **83.92 kJ/kg²**.

²Note: Since the water is referred to as "***saturated water***" and is clearly identified to be subcooled, the enthalpy value selected from the tables is **h_L** and not **h_v** .

Properties of Saturated Steam By Temperature									
Metric/SI Units									
Temp. °C	Abs. Press. MPa	Specific Volume m ³ /kg		Enthalpy kJ/kg			Entropy kJ/kg		Temp. °C
		Sat. Liquid <i>v_L</i>	Sat. Vapor <i>v_V</i>	Sat. Liquid <i>h_L</i>	Evap. <i>h_{fg}</i>	Sat. Vapor <i>h_V</i>	Sat. Liquid <i>s_L</i>	Sat. Vapor <i>s_V</i>	
20	0.002339	0.0010018	57.7610	83.920	2454.1	2537.5	0.2965	8.6661	20
50	0.012351	0.0010121	12.0280	209.34	2382.7	2591.3	0.7038	8.0749	50
100	0.101420	0.0010435	1.6719	419.10	2257.0	2675.6	1.3070	7.3541	100
200	1.554700	0.0011565	0.1272	852.39	1940.7	2792.1	2.3308	6.4303	200

Table 3.3 – Properties of Saturated Steam, by Temperature, SI Units

Quality of Steam Consideration in Thermodynamic Calculations:

In thermodynamics, there are myriad scenarios where water exists, simultaneously, in liquid and vapor forms. In such conditions, the concept of **quality** of steam plays a vital role. Quality, as described earlier is the ratio of the mass of vapor and the total mass of vapor and liquid. Mathematically, quality is defined as follows:

$$\text{Quality} = x = \frac{m_{\text{vapor}}}{m_{\text{vapor}} + m_{\text{liquid}}}$$

Where,

x = Quality, or quality factor

m_{vapor} = mass of vapor in the liquid and vapor mixture

m_{liquid} = mass of liquid in the liquid and vapor mixture

m_{liquid} + m_{vapor} = Total mass of the liquid and vapor mixture

When the quality of steam is less than one (1), or less than 100%, determination of enthalpy (and other parameters that define the state of water under those conditions) requires consideration of the proportionate amounts of saturated water (liquid) and vapor. For instance, if the quality of steam is 50%, determination of total enthalpy would entail 50% of the enthalpy contribution from saturated vapor and 50% from saturated water (liquid). This principle is formulated mathematically through Equations 3.2, 3.3, 3.4 and 3.5, and illustrated through Example 3.5.

The basic formulae for computing enthalpy, entropy, internal energy and specific volume when quality of steam is less than 100% are as follows:

$$\mathbf{h_x = (1-x) \cdot h_L + x \cdot h_v} \quad \mathbf{Eq. 3.2}$$

$$\mathbf{s_x = (1-x) \cdot s_L + x \cdot s_v} \quad \mathbf{Eq. 3.3}$$

$$\mathbf{u_x = (1-x) \cdot u_L + x \cdot u_v} \quad \mathbf{Eq. 3.4}$$

$$v_x = (1-x) \cdot v_L + x \cdot v_v \quad \text{Eq. 3.5}$$

Example 3.5:

Determine the enthalpy and specific volume for 100 psia steam with a quality of 55%.

Solution:

Given:

Quality, $x = 0.55$

Absolute Pressure = **100 psia**

From the saturated steam tables in Appendix B, and the excerpt in Table 3.4, the values of enthalpies and specific volumes, at 100 psia, are:

$$h_L = 298.57 \text{ BTU/lbm}$$

$$h_v = 1187.5 \text{ BTU/lbm}$$

$$v_L = 0.017736 \text{ ft}^3/\text{lbm}$$

$$v_v = 4.4324 \text{ ft}^3/\text{lbm}$$

Apply Equations 3.2 and 3.5, respectively:

$$h_x = (1-x) \cdot h_L + x \cdot h_v$$

$$v_x = (1-x) \cdot v_L + x \cdot v_v$$

Then,

$$h_x = (1 - 0.55) \cdot (298.57 \text{ BTU/lbm}) + (0.55) \cdot (1187.5 \text{ BTU/lbm})$$

$$h_x = 787.48 \text{ BTU/lbm}$$

And,

$$v_x = (1 - 0.55) \cdot (0.017736) + (0.55) \cdot (4.4324 \text{ ft}^3/\text{lbm})$$

$$v_x = 2.446 \text{ ft}^3/\text{lbm}$$

Properties of Saturated Steam By Pressure									
US/Imperial Units									
Abs. Press. psia	Temp. °F	Specific Volume ft ³ /lbm		Enthalpy Btu/lbm		Entropy Btu/(lbm.°R)		Abs. Press. psia	
		Sat. Liquid v_L	Sat. Vapor v	Sat. Liquid h_L	Evap. h_{fg}	Sat. Vapor h_V	Sat. Liquid s_L		Sat. Vapor s_V
1.0	101.69	0.016137	333.51	69.728	1036	1105.4	0.1326	1.9776	1.0
4.0	152.91	0.016356	90.628	120.89	1006.4	1126.9	0.2198	1.8621	4.0
14.0	209.52	0.016697	28.048	177.68	972.0	1149.4	0.3084	1.7605	14.0
100	327.82	0.017730	4.4324	298.57	889.2	1187.5	0.4744	1.6032	100

Table 3.4 – Properties of Saturated Steam, by Pressure, US Units

Properties of Saturated Steam By Temperature									
US/Imperial Units									
Temp. °F	Abs. Press. psia	Specific Volume ft ³ /lbm		Enthalpy Btu/lbm			Entropy Btu/(lbm.°R)		Temp. °F
		Sat. Liquid v_L	Sat. Vapor w	Sat. Liquid h_L	Evap. h_{fg}	Sat. Vapor h_V	Sat. Liquid s_L	Sat. Vapor s_V	
50	0.17813	0.016024	1702.9	18.066	1065.2	1083.1	0.0361	2.1257	50
100	0.95044	0.016131	349.87	68.037	1037.0	1104.7	0.1296	1.9819	100
210	14.1360	0.016701	27.796	178.17	971.6	1149.5	0.3092	1.7597	210
250	29.8430	0.017001	13.816	218.62	945.6	1164.0	0.3678	1.7000	250

Table 3.5 – Properties of Saturated Steam, by Temperature, US Units

Properties of Superheated Steam						
Metric/SI Units						
Abs. Press. MPa (Sat. T, °C)		Temp. °C				
		150	300	500	650	800
0.05 (81.33)	<i>v</i>	3.889	5.284	7.134		
	<i>h</i>	2780.1	3075.5	3488.7		
	<i>s</i>	7.9401	8.5373	9.1546		
0.1 (99.61)	<i>v</i>	1.9367	2.6398	3.5656		
	<i>h</i>	2776.6	3074.5	3488.1		
	<i>s</i>	7.6147	8.2171	8.8361		
1.0 (179.89)	<i>v</i>		0.2580	0.3541	0.4245	0.4944
	<i>h</i>		3051.7	3479.0	3810.5	4156.2
	<i>s</i>		7.1247	7.7640	8.1557	8.5024
2.5 (223.99)	<i>v</i>		0.0989	0.13998	0.1623	0.1896
	<i>h</i>		3008.8	3462.1	3799.7	4148.9
	<i>s</i>		6.6438	7.3234	7.7056	8.0559
3.0 (233.86)	<i>v</i>		0.0812	0.1162	0.1405	0.1642
	<i>h</i>		2994.3	3457.0	3797.0	4147.0
	<i>s</i>		6.5412	7.2356	7.6373	7.9885
4.0 (250.36)	<i>v</i>		0.0589	0.0864	0.1049	0.1229
	<i>h</i>		2961.7	3445.8	3790.2	4142.5
	<i>s</i>		6.3638	7.0919	7.4989	7.8523

Table 3.6 – Properties of Superheated Steam, SI Units

Properties of Superheated Steam						
US/Imperial Units						
Abs. Press. psia (Sat. T, °F)		Temp. °F				
		200	300	500	1000	1500
10 (193.16)	<i>v</i>	38.851				
	<i>h</i>	1146.4				
	<i>s</i>	1.7926				
15 (212.99)	<i>v</i>		29.906	37.986	57.931	
	<i>h</i>		1192.7	1287.3	1534.7	
	<i>s</i>		1.8137	1.9243	2.1312	
100 (327.82)	<i>v</i>			5.5875	8.6576	
	<i>h</i>			1279.3	1532.3	
	<i>s</i>			1.7089	1.9209	
200 (381.81)	<i>v</i>			2.7246	4.3098	
	<i>h</i>			1269.1	1529.5	
	<i>s</i>			1.6243	1.8430	
360 (434.43)	<i>v</i>			1.4460	2.3774	3.2291
	<i>h</i>			1250.6	1525.0	1799.8
	<i>s</i>			1.5446	1.7758	1.9375

Table 3.7 – Properties of Superheated Steam, US Units. *v* = specific volume in ft³/lbm; *h* = enthalpy in BTU/lbm; *s* = entropy in BTU/lbm-°R

Example 3.6:

Prove the equivalence of the Mollier Diagram and the Steam Tables by verifying the results of Example 2.1, Segment 2, through the use of Steam Tables in Appendix B.

Solution:

The solution from Example 2.1, as restated with the aid of Figure 3.1, is as follows:

$$h_i = \text{Enthalpy at } 450^\circ\text{C and } 1 \text{ Atm., as read from the Mollier Diagram} \\ = \mathbf{3380 \text{ kJ/kg}}$$

$$h_f = \text{Enthalpy at } 400^\circ\text{C and } 1 \text{ Atm., as read from the Mollier Diagram} \\ = \mathbf{3280 \text{ kJ/kg}}$$

Then, **using the Mollier Diagram**, the amount of heat that must be removed from the system in order to lower the temperature from 450°C to 400°C , at 1 Atm, would be:

$$\Delta h = h_i - h_f = 3380 \text{ kJ/kg} - 3280 \text{ kJ/kg} = \mathbf{100 \text{ kJ/kg}}$$

Now, lets determine the amount of heat to be removed using the **steam tables**, in Appendix B:

$$h_i = \text{Enthalpy at } 450^\circ\text{C and } 1 \text{ Atm., from Appendix B} \\ = \mathbf{3382.8 \text{ kJ/kg}}$$

$$h_f = \text{Enthalpy at } 400^\circ\text{C and } 1 \text{ Atm., from Appendix B} \\ = \mathbf{3278.5 \text{ kJ/kg}}$$

So, **using the Steam Tables**, the amount of heat that must be removed from the system in order to lower the temperature from 450°C to 400°C , at 1 Atm, would be:

$$\Delta h = h_i - h_f = 3382.8 \text{ kJ/kg} - 3278.5 \text{ kJ/kg} = \mathbf{104.3 \text{ kJ/kg}}$$

Therefore, for most practical purposes, the Mollier Diagram and the Steam Tables are equivalent insofar as thermodynamic system analyses are concerned. The 4.3% difference between the two approaches is due mainly to the small amount of inaccuracy in reading of the scale of the Mollier Diagram.

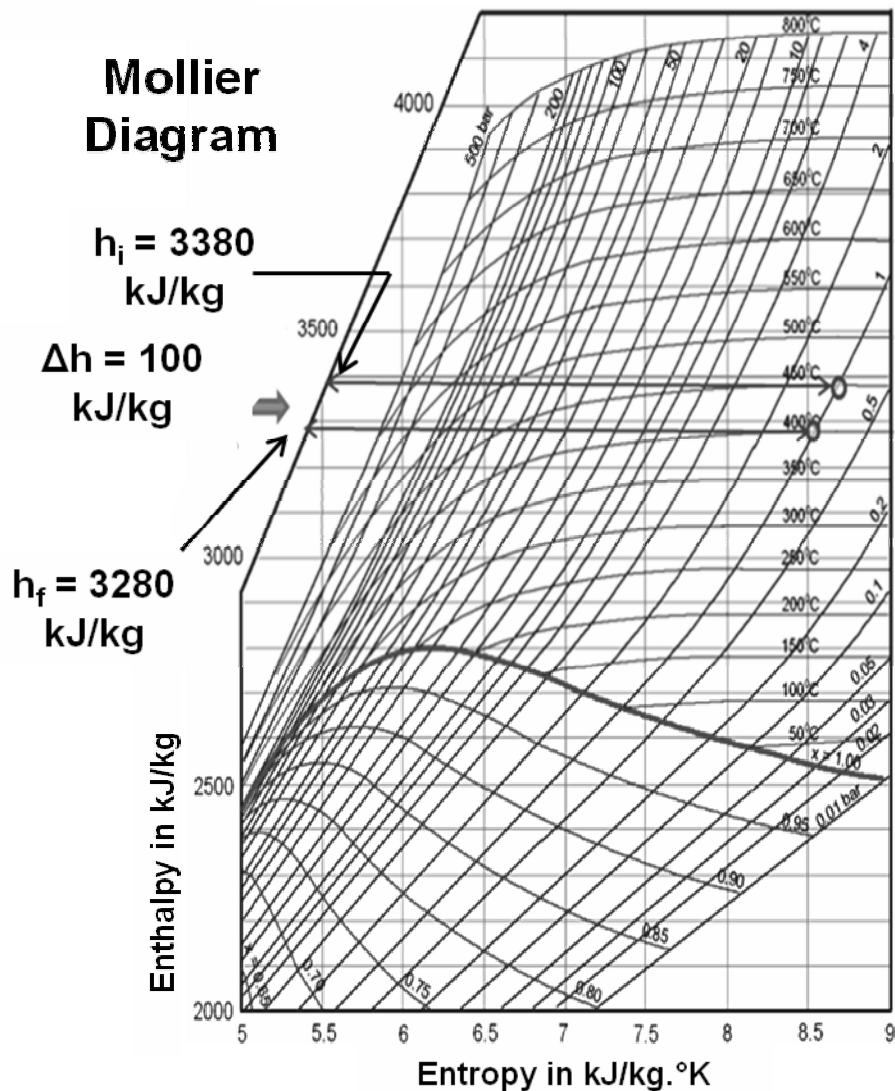


Figure 3.1 – Mollier Diagram, SI/Metric Units

Segment 3

Self Assessment Problems & Questions

1. Using the saturated liquid enthalpy value for h_L and the saturated vapor enthalpy value for h_V , at 0.2 MPa and 120.2°C, as listed in the saturated steam tables in Appendix B, calculate the value for h_{fg} .
2. Calculate the enthalpy of 450 psia and 970°F superheated steam.
3. Determine the enthalpy of saturated water at 50°C and 1 Bar.
4. Determine the enthalpy and specific volume for 14 psia steam with a quality of 65%.

APPENDICES

Appendix A Solutions for Self-Assessment Problems

This appendix includes the solutions and answers to end of segment self-assessment problems and questions.

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Appendix B Steam Tables

These steam tables, copyright ASME, published with ASME permission, do not include the heat of evaporation value, h_{fg} , values for the saturation temperature and pressures. The saturated steam tables presented in this text are the compact version. However, the h_{fg} values can be derived by simply subtracting the available values of h_L from h_v , for the respective saturation pressures and temperatures. In other words: $h_{fg} = h_v - h_L$

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Appendix C Common Units and Unit Conversion Factors

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Appendix D Common Symbols

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