



Fundamentals of Refrigeration

Thermo and HX



What you will Learn in this Lesson

- Thermodynamic properties of fluids
- Heat balance
- P-H diagrams
- Laws of thermodynamics
- Principles of heat transfer
- Heat exchangers

Thermodynamics

- Definition – “*The study of heat and work*”

Thermodynamics

Substance Properties – *“Any identifiable characteristic of a fluid”*

- Examples include
 - Pressure (p) – force over unit area (psi or Pa)
 - Can be absolute (based on zero) or gauge (based on 14.696 psi)
 - 20 psig = 34.7 psia
 - Temperature (T) – average motion of molecules in a fluid (°F or °C)
 - Volume (V) – geometric space occupied by a fluid (ft³ or m³)
 - Mass (m) - quantity of a substance (lb or kg)
 - Density (d) – mass divided by volume (lb/ft³ or kg/m³)
- Thermodynamic state is known for a simple fluid when two of the states are known

Thermodynamics

- **Sensible Heat** – *“Heat that raises or lowers the temperature of a substance”*
- **Latent Heat** - *“Heat that changes the state of a substance”*
 - Latent heat transfer will not change the temperature of the substance
 - Latent heat can be substantial

Thermodynamic Properties of Fluids

- **Specific Heat** – *“Energy required to raise the temperature on a known amount of substance 1 degree”*
 - Raise 1 lb water 1 F requires 1.0099 Btu
 - Specific heat (c_p) at constant pressure are used for flowing substances (refrigerants)
 - Specific heat (c_v) at constant volume are used for fixed amounts of substances (ice tank)

Substance	c_p (Btu/lb°F)		C_v (Btu/lb°F)	
	Liquid	Vapor	Liquid	Vapor
R-22	0.2798	0.1777	0.2161	0.1373
R-134a	0.3188	0.2109	0.2706	0.1791
Water	1.0099	0.4461	0.7594	0.3355
Air	-	0.2359	-	0.1710

Thermodynamic Properties of Fluids

$$Q = m \cdot c_p (T_2 - T_1)$$

Where:

Q = heat transfer rate (Btu/s)

m = mass flow rate (lb/s)

T = entering or leaving temperature (F)

Thermodynamic Properties of Fluids

$$Q = m \cdot c_p (T_2 - T_1)$$

$$Q \text{ (Btu/h)} = 500 \cdot \text{USgpm} (T_2 - T_1)$$

$$Q \text{ (tons)} = \text{USgpm} (T_2 - T_1) / 24$$

Based on:

Water (no glycol)

USgpm

F Temperatures

Thermodynamic Properties of Fluids

- **Saturation Condition** – *“When a liquid and vapor of the same substance are in contact with each other and all properties are constant with time, the substance is in equilibrium and is saturated”*

Thermodynamic Properties of Fluids

- **Saturation Condition** – *“When a liquid and vapor on the same substance are in contact with each other and all properties are constant with time, the substance is in equilibrium and is saturated”*
- At every saturated temperature, there is only one pressure.
 - Plotting the data for all temperatures will the dome of a P-H diagram

Enthalpy

Enthalpy (h) – *“Sum of internal energy and flow work of a substance”*

$$h = u + p \cdot v$$

Where

h = enthalpy (Btu/lb)

u = internal energy (Btu/lb)

p = pressure (psi)

v = specific volume (ft³/lb)

Saturated Refrigerant Properties

Temp	Pressure	Density	Volume	Enthalpy		Entropy		Specific Heat		Sound Spd.		Viscosity		Therm. Cond.	
[F]	[psia]	[lb/ft ³]	[ft ³ /lb]	[Btu/R-lb]		[Btu/R-lb]		[Btu/lb-°F]		[ft/s]		[lbm/ft-h]		[Btu/h-ft-R]	
		(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)	(L)	(V)
-153.5	0.057	99.34	561.85	-32.99	80.36	-0.09154	.2793	0.283	0.1399	3723	416	5.262	0.0156	0.084	0.00178
-150	0.072	98.97	452.1	-31.88	80.91	-0.08791	0.2763	0.283	0.1411	3638	418.3	4.7916	0.01584	0.0832	0.00188
-145	0.0968	98.51	341.4	-30.46	81.6	-0.08338	0.2728	0.2832	0.1427	3592	421.3	4.2912	0.016128	0.08223	0.00201
-140	0.1288	98.05	260.6	-29.05	82.3	-0.07891	0.2694	0.2834	0.1443	3545	424.2	3.8808	0.016452	0.08126	0.00214
-135	0.1696	97.59	201	-27.63	83.01	-0.07451	0.2663	0.2838	0.1459	3499					

Two Phase Refrigerants

Quality (x) – *“The ratio of vapor to liquid by mass”*

$$x = (h - h_l) / (h_v - h_l)$$

- Where:
 - X = Quality
 - h = enthalpy of the fluid (Btu/lb)
 - h_l = Saturated liquid enthalpy of the fluid at the same pressure or temperature (Btu/lb)
 - h_v = Saturated vapor enthalpy of the fluid at the same pressure or temperature (Btu/lb)

Entropy

Entropy (s) – *“The measure of the molecular disorder of a substance”*

- Measured in Btu/lb· R from a arbitrary point
- The more mixed a substance is the greater the entropy
- The more orderly a substance is the lower the entropy
- An **Isentropic Process** has the same entropy at the finish as at the start
 - It is a perfect process
 - It has no losses
 - It does not exist!

Laws of Thermodynamics

The First Law – “*Energy (mass) cannot be created or destroyed*”

- Also known as the “*Law of Conservation of Energy*”

Second Law of Thermodynamics

- *“A law stating that mechanical work can be derived from a body only when that body interacts with another at a lower temperature; any spontaneous process results in an increase of entropy”*
- *“With each change in form, some energy is degraded to a less useful form and given off into the surroundings, usually as low-quality heat.”*
- *“Heat cannot, of itself, pass from a colder to a hotter body.”*
- *“The disorder in the universe always increases.”*

Second Law of Thermodynamics

- Quantifies ***reversible*** from ***irreversible*** processes
 - Reversible process can return to the same starting point without adding energy
 - A reversible (perfect) spring would return all the energy stored during compression
 - A real (irreversible) spring would lose energy as heat, sound etc

Thermodynamic Laws

The first law says you cannot get something for nothing.

The second law says you cannot even come close.

Carnot Example

Calculate the carnot efficiency at standard chiller conditions

The heat absorption sink is 45°F or 505°R

The heat rejection sink is 95°F or 555°R

$$\text{COP}_{\text{carnot}} = \text{TR} / (T_{\text{O}} - T_{\text{R}}) = 505 / (555 - 505) = 10.1$$

$$\text{kW/ton} = 3.516 / 10.1 = 0.348 \text{ kW/ton}$$

Heat Transfer

Heat Transfer – *“Transition of thermal energy from a hotter mass to a cooler mass”*

- Must be a temperature gradient
 - Zeroeth Law states two objects in contact with each other but with no heat transfer are at the same temperature
- Heat can be transferred by;
 - Conduction
 - Convection
 - Radiation
- Generally, real world heat transfer includes all three processes at once

Heat Transfer

Conduction – *“Heat transfer between two objects in contact that have a temperature difference”*

$$q = (k \cdot A / t) \cdot (T_2 - T_1)$$

Where:

q = heat flow rate (Btu/hr)

A = area available for heat transfer (ft²)

t = thickness of material (ft)

k = thermal conductivity coefficient (Btu/h·ft· F)

(T₂ – T₁) = overall temperature difference (F)

HVAC Example

Heat transfer through a wall

Heat Transfer

Materials with high k values transfer heat faster
e.g. copper

The greater the area, the greater the heat transfer
e.g. more rows in a cooling coil

The thicker the material, the more resistance to heat transfer
e.g. thicker walls in a house

$$k \cdot A / t$$

Opposite of conductivity is resistance (R)

$$R = t / k \cdot A$$

e.g. “R value” for insulation

Heat Transfer

Radiation – *“Heat transfer from a location of higher temperature to a location of lower temperature by means of electromagnetic radiation ”*

- Not a major factor in refrigeration systems

HVAC Example

Radiant heating panels
or infrared heater

Heat Transfer

Convection – *“Heat transfer between two fluids in motion”*

$$q = h_c \cdot A(T_2 - T_1)$$

Where:

Q = heat flow rate (Btu/hr)

A = area available for heat transfer (ft²)

h_c = convection heat transfer coefficient (Btu/h·ft²· F)

($T_2 - T_1$) = overall temperature difference (F)

HVAC Example

Air flowing over a
heating coil

Heat Transfer

- Different fluids have different convective heat transfer coefficients
- Overall performance affected by
 - Specific heat (c_p)
 - Viscosity (μ)
 - Thermal conductivity (k)
- Best fluids have
 - High specific heat
 - Good thermal conductivity
 - Low viscosity
- Prandtl number ($Pr = \mu \cdot c_p / k$) is a measure of these properties

Laminar vs. Turbulent Flow

Reynolds Number (Re) – *“Dimensionless parameter that determines the behavior of viscous flow patterns ”*

$$Re = V \cdot D / \nu$$

Where

V = average fluid velocity (ft/s)

A = area available for heat transfer (ft²)

D = tube diameter (ft)

ν = kinematic viscosity (ft²/s)

Re values less than 2,300 considered laminar

Re values above 4,000 considered turbulent

Reynolds number

The greater the fluid velocity, the higher the Reynolds number

The greater the viscosity, the lower the Reynolds number.
Adding glycol to water will increase viscosity and lower the Reynolds number

$$V \cdot D / \nu$$

Overall Heat Transfer

$$q = U \cdot A (T_2 - T_1)$$

Where

Q = heat flow rate (Btu/hr)

A = area available for heat transfer (ft²)

U = overall heat transfer coefficient (Btu/h·ft²· F)

(T₂ - T₁) = overall temperature difference (F)

HVAC Example

Air flowing over a heating coil

- HVAC heat transfer processes are complex combination of all three transfer functions
 - U value is the sum of all processes

Overall Heat Transfer

Heat Transfer through Tube Wall

R= Resistance

$$R_{\text{Total}} = R_o + R_{\text{Tube}} + R_i$$

Given $R = 1/UA$

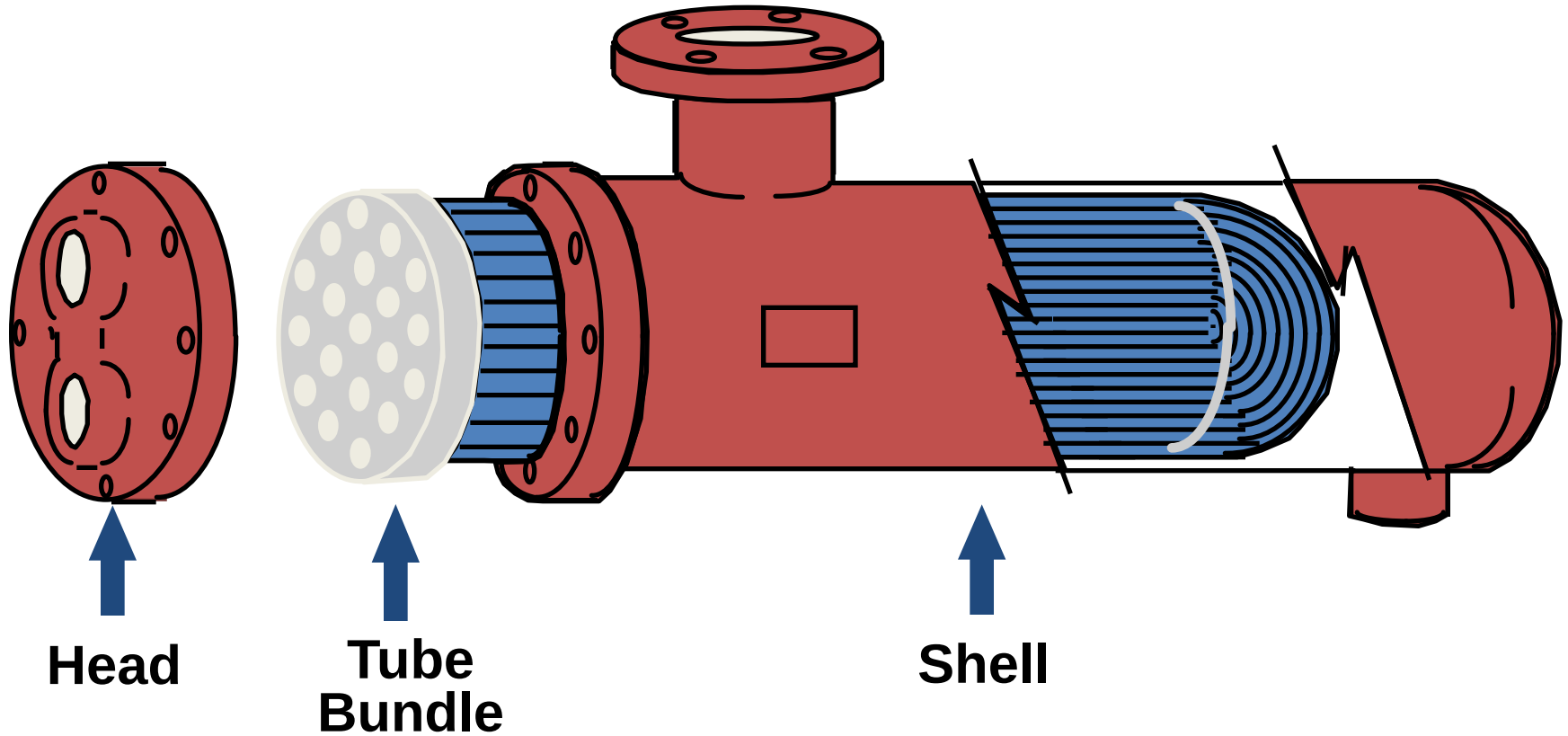
$$1/UA = 1/U_o A_o + t/kA_{\text{mean}} + 1/U_i A_i$$

Convective process
e.g. Water to tube

Conductive process
Through tube

Convective process
e.g. tube to refrigerant

Shell and Tube Heat Exchanger Detail



Log Mean Temperature Difference

$$q = U \cdot A \cdot \Delta T_{\text{mean}}$$

- Where
 - q = heat flow rate (Btu/hr)
 - A = area available for heat transfer (ft²)
 - U = overall heat transfer coefficient (Btu/h·ft²· F)
 - ΔT_{mean} = mean temperature difference (F)
- For ΔT_{mean} the **Log Mean Temperature Difference (LMTD)** is used

$$\text{LMTD} = (\theta_1 - \theta_2) / \ln(\theta_1 / \theta_2)$$

Heat Transfer Parameters

- **Temperature Difference ΔT**

- Can take the form of $(T_2 - T_1)$ or the log mean temperature difference
- Cutting the temperature difference in half, while maintaining the same heat transfer, will double the required surface area
- For cooling applications, the temperature differences are typically less than 10 F (5.6 C) so small temperature changes can greatly impact the size (and cost) of heat exchangers

- **Conductivity k**

- Some materials conduct heat better than others
- Copper and aluminum are good conductors while plastics generally are not
- Copper and aluminum are extensively used in heat exchangers. Where there are materials compatibility issues such as ammonia systems or bore hole fields for geothermal systems, other materials are used

HVAC Example

Deliver air cooled to 55 F using 45 °F chilled water. Raising water temperature 2 °F is a 20% reduction in ΔT .

HVAC Example

$$k_{\text{aluminum}} = 128 \text{ Btu/h}\cdot\text{ft}\cdot\text{F}$$

$$k_{\text{copper}} = 227 \text{ Btu/h}\cdot\text{ft}\cdot\text{°F}$$

$$k_{\text{steel}} = 26.2 \text{ Btu/h}\cdot\text{ft}\cdot\text{°F}$$

$$K_{\text{glass fiber}} = 0.026 \text{ Btu/h}\cdot\text{ft}\cdot\text{°F}$$

$$k_{\text{soil}} = 0.75 \text{ Btu/h}\cdot\text{ft}\cdot\text{°F}$$

Heat Transfer Parameters

- **Area A**
 - Doubling the area will double the heat transfer rate but will also mostly likely double the cost
- **Thickness t**
 - The thicker the tube wall, the poorer the heat transfer. A balance must be struck between tube robustness and heat transfer
- **Overall heat transfer coefficient U**
 - This coefficient is a summary of all the processes that affect heat transfer in a component
 - It can be experimentally measured and used for predicting other performance conditions

HVAC Example

Reduce leaving approach of cooling coil and see the rows increase

HVAC Example

Change the tube wall thickness in a chiller and water performance decrease

HVAC Example

Coat the heat exchanger tubes with oil and watch chiller performance decrease

Heat Transfer Parameters

- **Reynolds Number (Re)**

- Indicates whether the fluid is turbulent. Turbulence is required to achieve high levels of heat transfer
- When the system design allows fluid flow rates to vary (for example, variable primary flow) special care must be taken to make sure the fluids stay turbulent over the full operating range

- **Prandtl number (Pr)**

- indicates its quality as a heat transfer fluid. Prandtl numbers are defined as;
- $Pr = c_p \mu / k$
- Where
- c_p = fluid specific heat
- μ = fluid dynamic viscosity
- k = fluid conductivity
- High Pr means strong convective heat transfer

HVAC Example

“Must keep water velocity in evaporator above 3 fps”

Speaks to maintaining turbulent flow for water (not glycol!)

HVAC Example

$$Pr_{\text{water}} = \sim 7$$

$$Pr_{\text{air}} = \sim 0.7$$

$$Pr_{\text{refrigerant}} = \sim 4-5$$

$$Pr_{\text{oil}} = \sim 100 - 40,000$$

End of Lesson

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