Chapter Two

Properties of Ammonia

Physical Properties

General

Anhydrous ammonia exists as either a colorless gas, colorless liquid, or white solid, depending on its pressure and temperature. In nearly all commonly encountered situations, it exists as either a liquid or a gas. The gas is less dense than air and the liquid is less dense than water at standard conditions. Ammonia gas (vapor) diffuses readily in air and the liquid is highly soluble in water with an accompanying release of heat.

Ammonia exhibits classical saturation relationships whereby pressure and temperature are directly related so long as both the vapor and liquid phase are present. It does have a critical pressure and temperature. At atmospheric pressure, a closed container of ammonia vapor and liquid will be in equilibrium at a temperature of –28°F [–33°C]. It should be noted however that if liquid ammonia is spilled or released to the atmosphere at normal temperatures, the resultant pool of boiling liquid will be significantly colder than –28°F due to the law of partial pressures (the partial pressure of the ammonia vapor in the air near the liquid surface will be less than atmospheric pressure).

The following table provides some of the important physical properties of ammonia.

TABLE 2-1
Physical Properties of Ammonia

Property	Condition	Value (IP)	Value (SI)
Molecular Weight		17.03	17.03
Color		None	None
Physical State	Room Temp	Gas	Gas
Freezing Point	P=1 atm	–108°F	–78°C
Boiling Point	P=1 atm	–28.1°F	–33.3°C
Critical Pressure		1657 psia	11,410 kPa
Critical Temp		271°F	133°C
Specific Gravity	32°F/1 atm/vap	0.596	0.596
Specific Gravity	60°F/liquid	0.62	0.62
Specific Volume	32°F/1 atm/vap	20.8 ft^3/lb	1.30 m^3/kg
Odor Threshold		5–50 ppm	5–50 ppm
Upper Flam Lim		25–28%	25–28%
Lower Flam Lim		15–16%	15–16%
Ignition Temp	No Catalyst	1204°F	651°C

Thermodynamic Properties of Ammonia

Thermodynamic Property Tables

Reader is directed to *Appendix A* of this Data Book for an extensive set of Thermodynamic Property tables. For those using the thermodynamic properties for ammonia refrigeration cycle analysis, *Appendix B* contains a number of Ammonia Refrigeration Application Tables.

Ammonia and the Ideal Gas Relationship

It is oftentimes of interest to know how closely the properties of an actual gas can be approximated by the ideal gas equation:

$Pv = ZRT$
(For I-P units — psia, ft^3/pound, °Rankine):
$Pv = 0.6T_R$ (ZR = 0.60)

Some checks of actual data compared to that calculated by the ideal gas equation are shown in the following table.

TABLE 2-2
Ideal Gas Equation Accuracy

Known Conditions				Find	Calc Result $v = 0.6TR/P$	Actual from Property Tables
Saturated Vapor	Superheated Vapor	Psia	T	v		
√		14.7	-28F	?	17.6	18.0
√		66.3	35F	?	4.5	4.4
√		129.0	70F	?	2.5	2.3
√		180.6	90F	?	1.8	1.7
	√	42.0	100F	?	8.0	8.2
	√	42.0	200F	?	9.4	9.8
	√	130.0	150F	?	2.8	2.8
	√	200.0	300F	?	2.3	2.3

The above checks show that the ideal gas equation can be used with reasonable accuracy to approximate pressure, specific volume, or temperature if two of the three properties are known. Errors are greatest near the saturation line and at higher pressures. In the superheat area results are typically within 5% of actual. Refer to *Thermodynamic Properties of Ammonia as an Ideal Gas NSDS-NBS 19* (1968) by Lester Haar for a very detailed assessment of ideal gas relationships for ammonia.

Chemical Properties

Anhydrous ammonia is a naturally occurring compound comprised of two very common elements — nitrogen and hydrogen. The atmosphere is nearly 80% nitrogen, whereas hydrogen is a common element in many organic compounds. This helps to explain why ammonia is a vital chemical in both plant and animal life (*see Chapter 3 – Ammonia and the Environment*).

Ammonia is a four-atom molecule comprised of one nitrogen atom and three hydrogen atoms. The molecular weight is computed as shown in the following table.

TABLE 2-3
Molecular Weight

1 Nitrogen Atom x 14.007		14.007
3 Hydrogen Atoms x 1.008		3.024
	Total	**17.031**

Thus 1 gram-mole weighs 17.031 grams and 1 pound-mole weighs 17.031 pounds.

The following table contains some additional chemical data for ammonia taken from *Perry's Chemical Engineers' Handbook* (1997) and the Chemical Rubber Company *CRC Handbook of Chemistry and Physics* (1969).

TABLE 2-4
Ammonia Chemical Property Data

Property	Condition	Value
Heat of Formation	25°C	–10.96 kcal/mole
Free Energy of Formation	25°C	–3.903 kcal/mole
$Log_{10} K_f$	25°C	2.914
Dielectric Constant	–77.7°C Liquid	25.0
Dielectric Constant	–33.4°C Liquid	22.4
Dielectric Constant	5.0°C Liquid	18.9
Dielectric Constant	15.0°C Liquid	17.8
Dielectric Constant	25.0°C Liquid	16.9
Dielectric Constant	35.0°C Liquid	16.3
Dipole Moment	–	1.3×10^{-18} e.s.u.
Ionization Potential	–	11.2 volts
Magnetic Susceptibility	–	-18×10^{-6} cgs
Index of Refraction	Gas, white light	1.000383
Heat of Combustion	Net htg. value	8001 Btu/lb

Information from *Perry's Chemical Engineers' Handbook* is reproduced with permission of The McGraw-Hill Companies.

Hazardous Reactions

Ammonia is considered to be a relatively stable compound but this does not mean that ammonia does not participate in any hazardous or potentially hazardous reactions with other materials. The National Fire Protection Association (NFPA) has published *Fire Protection Guide to Hazardous Materials* (2001), which itemizes several reactions which could be hazardous. The following table summarizes those substances which can react hazardously with ammonia.

TABLE 2-5
Substances Reacting Hazardously with Ammonia

Acetaldehyde	Magnesium Perchlorate
Acrolein	Mercury
Boron	Nitric Acid
Boron Trioxide	Nitrogen Tetroxide
Bromine	Nitrogen Trifluoride
Caloric Acid	Nitryl Chloride
Chlorine	Oxygen Difluoride
Chlorine Monoxide	Phosphorous Pentoxide
Chlorine Trifluoride	Phosphorous Trioxide
Chlorites	Picric Acid
Chlorisilane	Potassium
Chromic Anhydride	Potassium Chlorate
Chromyl Chloride	Potassium Ferricyanide
Ethylene Dichloride	Potassium Mercuricyanide
Ethylene Oxide	Potassium Tricyanomercurate
Fluorine	Silver
Gold	Silver Chloride
Hexachloromelamine	Sodium
Hydrazide	Stilbene
Hydrogen Bromide	Sulfur
Hypochlorous Acid	Tellurium
Iodine	Trichloromelamine

Compatibility

Ammonia reacts readily with a wide variety of substances. Ammonia is incompatible with copper, zinc, or copper-based alloys, and corrosion of these metals will occur. However, there are journal bearings, thrust washers, and piston rings containing copper bearing materials used within ammonia compressors which are acceptable since they are continually coated with lubricating oil and no degrading chemical reaction occurs. Ammonia is compatible with aluminum, steel, and stainless steels. Certain high tensile strength steels can experience stress corrosion cracking if the ammonia is totally anhydrous. The susceptibility of carbon steels to stress corrosion cracking increases with higher strength steels, particularly in situations with high residual or applied stresses. The susceptibility to stress corrosion cracking is enhanced when the concentration of oxygen is as low as 0.5 ppm (Bansch 2007) and becomes more inhibited with increasing concentration of water to approximately 0.2%. Ammonia is soluble in water, alcohol, ether, and other organic solvents. It is virtually immiscible with most mineral-based lubricating oils although liquid ammonia will physically carry oil along as it flows.

Ammonia exhibits varying degrees of compatibility with elastomers that are commonly used as gaskets and valve trim. Compatibility for various elastomers along with the functional service temperature range is given in the following table (Fisher Controls Company 1977).

TABLE 2-6
Elastomer/Ammonia Compatibility

Material	Compatibility
Natural Rubber	Not recommended.
Neoprene	Acceptable at lower temperatures. Marginal at higher temperatures. Buna N o-rings are acceptable and are used by some manufacturers of ammonia compressors. Recommended service temperature limits of –40°F to 175°F.
Nitrile	Not recommended.
Ethylene Propylene	Acceptable at lower temperatures. Marginal at higher temperatures. Recommended service temperature limits of –40°F to 300°F.
Polyurethane	Not recommended.
Hypalon	Marginal. Recommended service temperature limits of 0°F to 225°F.
Butyl	Acceptable at lower temperatures. Not recommended at higher temperatures. Recommended service temperature limits of –20°F to 300°F.
Silicone	Not recommended at low temperatures. Marginal at higher temperatures. Service temperature limits of –65°F to 400°F.
Teflon	Although technically not an elastomer, it is highly compatible with ammonia and is recommended as a valve seat material within the overall service temperature range of teflon.
Viton	Not recommended.

Stress Corrosion Cracking of Steel

Stress corrosion cracking (SCC) is a generic term describing both the initiation and propagation of cracks in a metal or alloy influenced by a combination of tensile stress in the presence of an encouraging chemical environment (Hogan 1959, Bates and Loginow 1964, Hehemann 1985, Stafford and Mueller 1992, Vander Voort 2002, and others). Bansch (2007) and Pearson (2007) separately reviewed cases of stress corrosion cracking of carbon steel materials used in ammonia service. The susceptibility of a material to exhibit stress corrosion cracking depends on the presence of three distinct factors (Bansch 2007):

1. Material — higher yield strength materials are more susceptible to stress corrosion cracking
2. Environment — an enabling chemical environment for ammonia refrigeration systems shows an increased tendency towards stress corrosion cracking when oxygen is present with water as an inhibitor
3. Stress — the susceptibility of a material to stress corrosion cracking increases with increasing applied stress where the stress could be due to pressure, static loading, dynamic loading, and residual stresses that result from welding and/or forming.

The risks of stress corrosion cracking can be reduced or eliminated by addressing one or more of the above mentioned factors. Recent recommendations to prevent stress corrosion cracking in ammonia refrigeration systems have been made by the IIAR Stress Corrosion Cracking taskforce, Bansch (2007), Pearson (2007) and IRC (2005), and can be summarized by the following:

Material — lower yield strength materials are less susceptible to stress corrosion cracking. Where possible, specify a carbon steel with a minimum yield stress that does not exceed 50 ksi [350 MPa]. As Bansch (2007) points out, "the most economical and widely available steel plate suitable for refrigeration pressure vessels is SA516-70. The minimum yield strength of 262 MPa [38,000 psi] categorizes SA516-70 as a low to medium strength steel which is less susceptible to SCC. Actual yield strengths may be significantly higher; up to 386 MPa [56,000 psi] is common, with some yield strengths as high as 435 MPa [63,000 psi]." Unfortunately, the volume of steel consumed by the refrigeration industry is quite small making the prospect of dictating or hand-selecting lower yield strength steel specifically for vessel construction not practical.

Post-weld heat treatment — One of the most effective approaches to reduce the likelihood of stress corrosion cracking is to stress relieve vessels following the construction process. The use of hot-formed heads is recommended followed by post weld heat treatment of the entire vessel to relieve the residual stress of welding and forming. Exceptions should be made for compressor oil separators and specialized vessels, such as plate heat exchangers, containing internal components that could be damaged, e.g. internal bushings, gaskets, etc.

Non-condensable gases — The presence of non-condensable gases (specifically, oxygen) increases the probability of SCC. As such, purging of air from the system during both initial start-up and during operation and maintenance is important. At initial start-up and during commissioning, adhere to evacuation recommendations in IIAR Bulletin 110 (IIAR, 2004). During refrigeration system operation, maintain effective air purging.

Common Reactions Involving Ammonia

While there are many hundreds of possible reactions involving ammonia, some of the more common and commercially important ones are presented here.

TABLE 2-7
Common Reactions Involving Ammonia

Reaction Description	Chemical Formula
Nitric acid can be produced by oxidizing ammonia in the presence of a platinum-rhodium catalyst.	$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$ $2NO + O_2 \rightarrow 2NO_2$ $3NO_2 + H_2O \rightarrow 2HNO_3 + NO$
The ability of ammonia to neutralize acids is of great commercial importance to the fertilizer industry. Three major fertilizers, ammonium nitrate, ammonium sulfate, and ammonium phosphate are produced by reaction of ammonia with nitric, sulfuric, and phosphoric acid.	$HNO_3 + NH_3 \rightarrow NH_4 NO_3$ $H_2SO_4 + 2NH_3 \rightarrow (NH_4)_2SO_4$ $H_3PO_4 + 3NH_3 \rightarrow (NH_4)_3PO_4$
Amides of potassium and sodium can be generated by dissolving the metal in liquid ammonia.	$2Na + 2NH_3 \rightarrow 2NaNH_2 + H_2$ $2K + 2NH_3 \rightarrow 2KNH_2 + H_2$
The amides of the alkali metals can be produced by double-decomposition reactions in liquid ammonia.	(liq NH_3) $NaI + KNH_2 \rightarrow NaNH_2 + KI$
Nitride can be produced by heating ammonia with a more active metal such as magnesium.	$3Mg + 2NH_3 \rightarrow Mg_3N_2 + 3H_2$
Sulfur vapor and ammonia react to give ammonium sulfide and nitrogen. Sulfur also reacts with liquid ammonia to produce nitrogen sulfide.	$10S + 4NH_3 \rightarrow 6H_2S + N_4S_4$
Ammonia and phosphorus vapor at red heat yields nitrogen and phosphine.	$2NH_3 + 2P \rightarrow 2PH_3 + N_2$
Ammonia reacts with carbon dioxide to make ammonium carbamate.	$2NH_3 + CO_2 \rightarrow NH_2CO_2NH_4$ which then decomposes to urea and water $NH_2 CO_2 NH_4 \rightarrow NH_2 CONH_2 + H_2O$
Carbon dioxide, ammonia, and water vapor react to form ammonium carbonate. This reaction can be important when dealing with ammonia leaks and spills.	$O_2 + 4CO_2 + 2H_2O + 4NH_3 \rightarrow 4NH_4 CO_3$

Flammability

Although ammonia is designated as a non-flammable gas for shipping purposes by the United Nations and the U.S. Department of Transportation, it is flammable in air within a certain range of concentrations. Because these concentrations are quite high, it would be extremely difficult to reach those conditions in an outdoor shipping situation. The fact that ammonia gas is lighter than air and that it diffuses readily in air makes it difficult to create a flammable situation outdoors.

In confined spaces, vessels, or in controlled process conditions, it is possible to ignite gaseous ammonia. Different sources list different flammability limits for ammonia. The likely explanation for the discrepancy between these published limits of flammability is that the test procedures have changed and/or have become more technologically advanced. Older flammability limits for ammonia (Bureau of Mines 1931) were expressed as follows:

- Lower flammability limit 16%
- Upper flammability limit 25%

The more current NFPA *Fire Protection Guide to Hazardous Materials* (2001), now lists ammonia's flammability limits as:

- Lower flammability limit 15%
- Upper flammability limit 28%

NFPA does not indicate the source of the newer limits but these limits are consistent with the findings of two German researchers who published a paper in 1980 entitled *Determination of Explosion Limits of Ammonia in Mixtures with Simple Hydrocarbons and Air* (Kalbert and Schecher 1980). These same tests found that the flammability limits of ammonia/hydrocarbon/air mixtures follow Le Chatelier's Law governing mixtures of combustible gases quite well. The net result is that the presence of hydrocarbons can significantly lower the ammonia concentration required to create a flammable situation.

This same German research also measured explosion pressures both in terms of peak pressure and rate of pressure rise. These tests confirmed that ammonia explosions result in lower peak pressures and slower rates of pressure rise than do methane explosions.

TABLE 2-8
Explosion Pressures

Explosion Characteristic	Methane	Ammonia
Peak Pressure	~105 psig	~60 psig
Rate of Pressure Rise	3000 psi/second	440 psi/second

More recent tests conducted as part of ASHRAE sponsored research at Kansas State University found the flammability limits to be 15% and 27.4% with dry air. Although humidity and temperature are thought to affect the flammability limits, conclusive results have not yet been obtained (Khan et. al. 1995).

In summary, humidity and temperature are generally considered to be factors which result in these limit ranges:

- Lower flammability limit 15–16%
- Upper flammability limit 25–28%

Ammonia explosions are technically termed deflagrations because the propagation speed of the combustion zone is less than the speed of sound. Explosions involving the more flammable fuel gases such as methane are termed detonations because the propagation velocity exceeds the speed of sound.

Ammonia can be purposefully burned or flared in a controlled process. The following table contains some of the pertinent combustion data for ammonia gas. The numbers in this table can also be found in *Thermodynamics, an Engineering Approach* (Cengel and Boles 1989).

TABLE 2-9
Ammonia Combustion Data

Combustion Parameter	Value
Gross Btu/lb	9,668
Net Btu/lb	8,001
Air Required (lb/lb)	6.10
Comb. Products (lb/lb)	
Water	1.59
Nitrogen	5.51

Efforts to ignite a standing pool of liquid ammonia in an outdoor situation have not been successful.

Explosion Venting

Rooms or enclosures subject to explosive concentrations of ammonia due to leaks or releases can be designed to relieve the deflagration energy in a controlled fashion via properly designed explosion venting in the enclosure envelope.

NFPA has published guidelines for the design of explosion venting systems in NFPA 68, *Standard on Explosion Protection by Deflagration Venting* (NFPA 2007). They have developed an equation for calculating the venting area (A_v) as a function of total internal surface area of enclosure (A_s), the maximum internal overpressure that could be withstood by the weakest non-venting structural element of the enclosure (P_{red}), and a venting equation constant (C) for the gas mixture of interest.

The subjects of explosion suppression and deflagration pressure containment are addressed in NFPA 69 *Standard on Explosion Prevention Systems* (NFPA 2008). It specifically covers the design of ventilation systems needed to prevent build-up of explosive concentrations.

Transport/Thermophysical Properties

General

The subject of transport phenomena covers the fields of heat transfer, mass transfer, and momentum transfer. These transfer mechanisms are governed by a variety of key properties of ammonia. These properties in turn are often grouped into dimensionless groups, such as Reynolds numbers, in order to predict the transfer rates of heat, mass, and momentum.

The *Thermophysical Properties of Refrigerants* (Liley and Desai, 1993) is the best overall collection of information. A number of transport properties are dependent on the pressure and temperature of the gas or liquid. Several of these properties have been depicted graphically herein. ASHRAE also suggests some relatively complex polynomial correlations suitable for computerized applications requiring high levels of accuracy.

Thermal Conductivity (k)   Both ammonia gas and liquid have high thermal conductivities (k) relative to most other compounds. This attribute gives ammonia excellent heat transfer characteristics.

Refer to the following graphs for the thermal conductivity of ammonia liquid and for the thermal conductivity of ammonia gas/vapor.

FIGURE 2-1 Thermal Conductivity of Ammonia Liquid
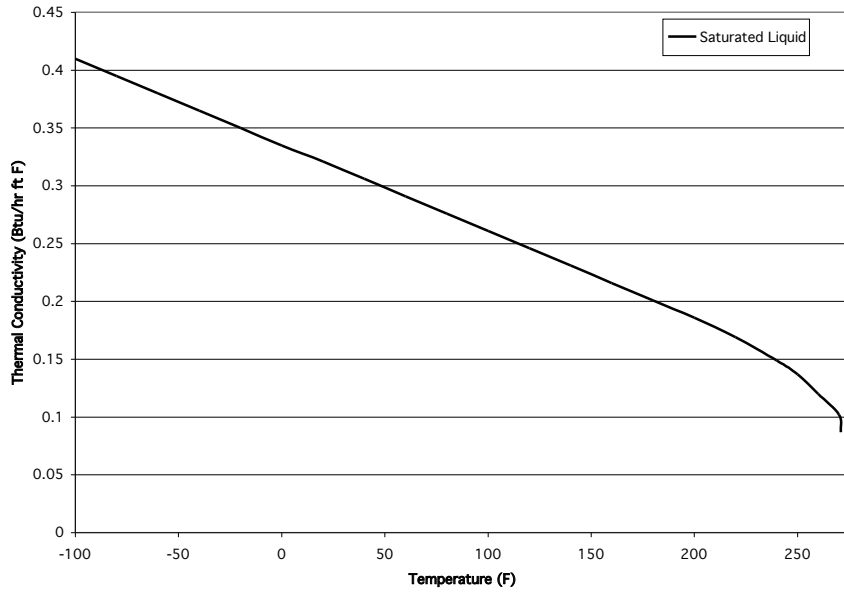
FIGURE 2-2 Thermal Conductivity of Ammonia Gas/Vapor
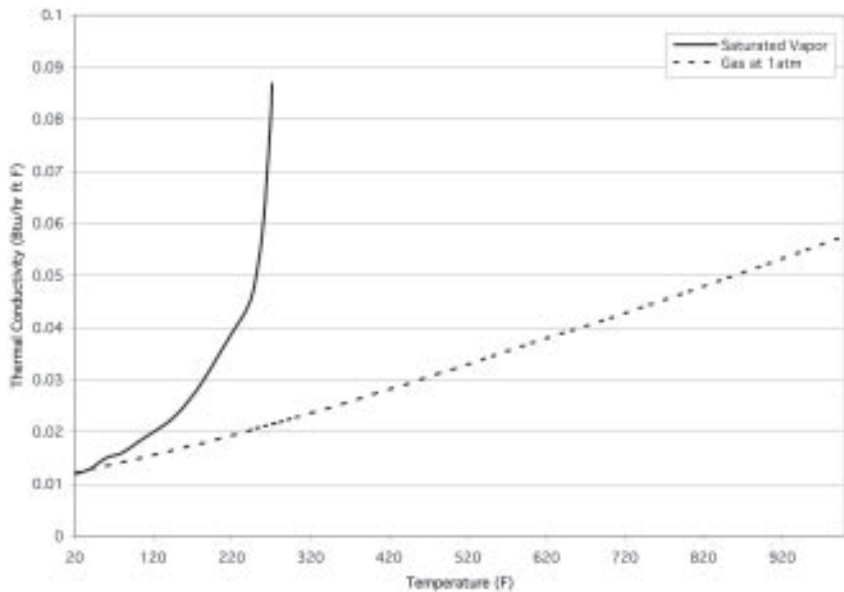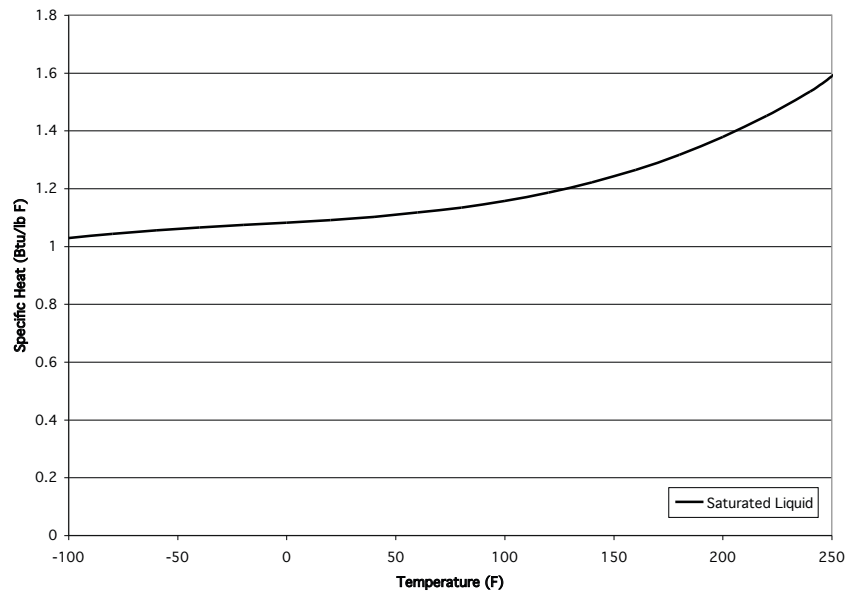
Specific Heat
(Heat Capacity-c_p)

Both ammonia gas and liquid have high specific heats or heat capacities (c_p) compared to most other compounds. This characteristic makes ammonia an excellent heat transfer fluid.

Refer to the following graphs for the specific heat of ammonia liquid and the specific heat of ammonia gas/vapor.
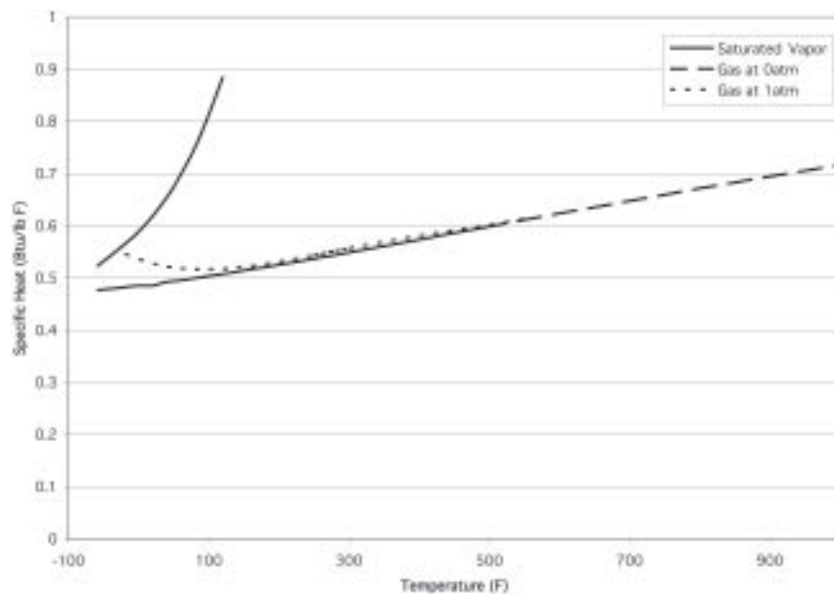
Perry's Chemical Engineers' Handbook (1997) lists the following relationship for specific heat of gas/vapor as a function of temperature (K) for the range of 300–800K:

$$c_p = 0.393 + 0.00037 T_K \quad (cal/g°C)$$
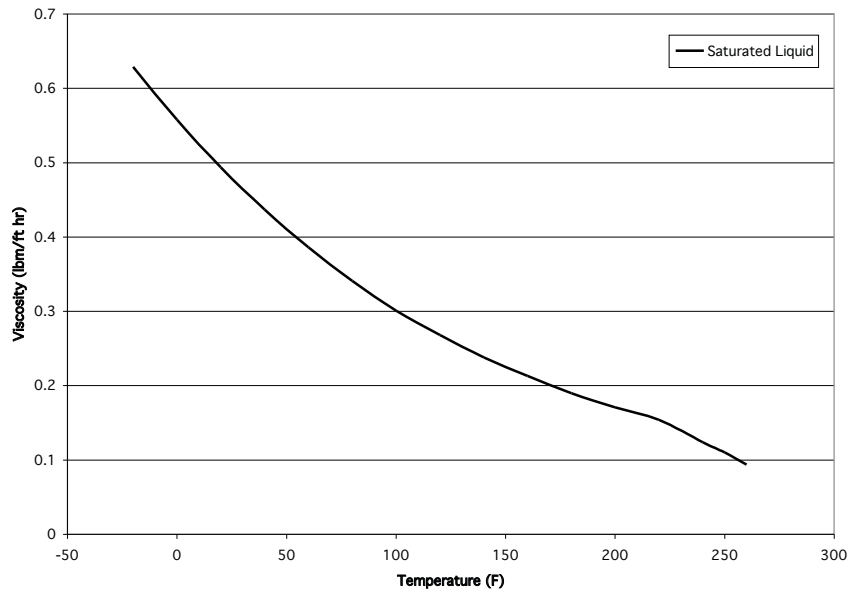
FIGURE 2-3 Specific Heat of Ammonia Liquid
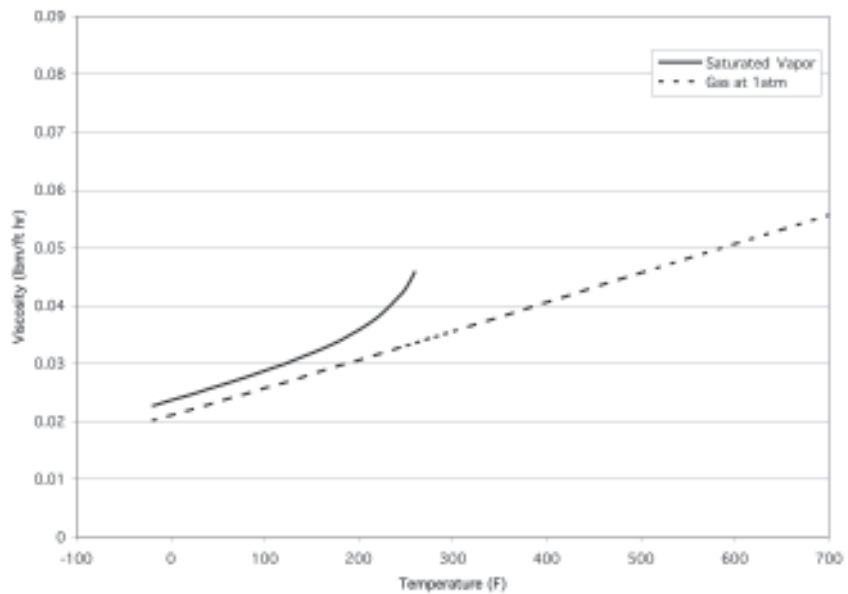

FIGURE 2-4 Specific Heat of Ammonia Gas/Vapor

Viscosity (µ)

The viscosity (µ) of ammonia gas and liquid is about average compared to other fluids. Refer to the following graphs for the viscosity of ammonia liquid and the viscosity of ammonia gas/vapor.

FIGURE 2-5 Viscosity of Ammonia Liquid

FIGURE 2-6 Viscosity of Ammonia Gas/Vapor

Heat Capacity Ratio (k)*

There are numerous equations and relationships that use k (dimensionless) which is the ratio of the specific heat at constant pressure to the specific heat at constant volume. According to *Perry's Chemical Engineers' Handbook* (1997), a good average value of k for ammonia vapor is 1.3. Using REFPROP 7 (NIST 2002) for ammonia vapor at several constant temperatures with pressure ranging from 1.0 psia to the corresponding saturated vapor pressure shows that as the saturated vapor condition is approached, k increases somewhat. The *ASHRAE Fundamentals Handbook* (2005) gives values of k for saturated ammonia vapor as a function of temperature. An excerpt of these values is shown in the table below where k is noted to increase slightly with saturated temperature:

FIGURE 2-7 Heat Capacity Ratio with Pressure and Temperature
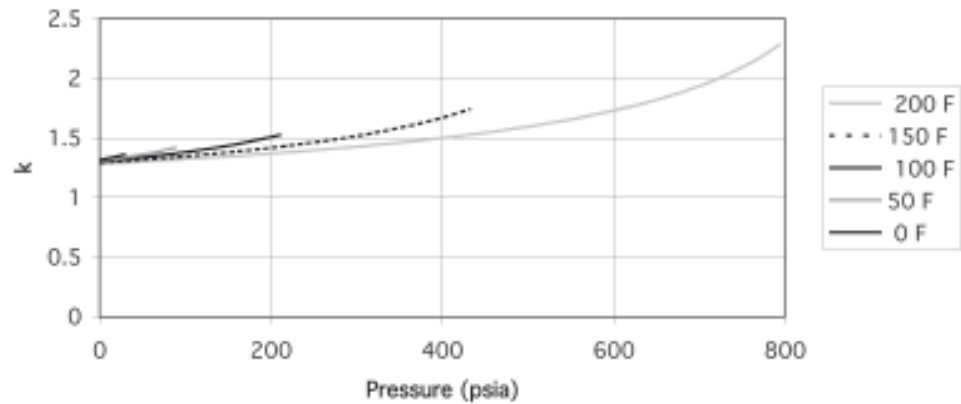
* The Greek symbol γ is also used to represent the heat capacity ratio in many publications.

Variation of k for Saturated Ammonia Vapor with Temperature:

T (°F)	k
−100	1.3262
−50	1.3379
0	1.3657
50	1.4222
100	1.529
150	1.724
200	2.290
250	5.420

Velocity of Sound in Ammonia   (@ 32°F) = 1361 ft/s [415 m/s] (in gas — CRC 1969)

V = 4900 ft/s [1494 m/s] (in liquid — Chaudry 1987)

The acoustic velocity is proportional to the square root of the absolute temperature for the gas:

$$c_{ideal} = \sqrt{\frac{\gamma RT}{M}}$$

In situations when real gas effects are important and ideal gas behavior cannot be assumed, including when liquid is present, the acoustic velocity becomes:

$$c = \sqrt{\frac{K_s}{\rho}}$$

where K_s is the isentropic bulk modulus and ρ is the density of the fluid.

Critical Pressure Ratio (r_c)   The critical pressure ratio (r_c) is the ratio of absolute pressures that will accelerate a gas to the acoustic velocity in a frictionless nozzle. At this condition, the nozzle is said to be "choked." Any pressure ratio greater than r_c will not result in a greater mass flow rate through the nozzle when upstream stagnation temperature and pressure remain the same. The relationship for r_c of an ideal gas is representative for ammonia (Perry 1997):

$$r_c = \frac{2^{\frac{k}{k+1}}}{k-1} = 0.55$$

Surface Tension (σ)

Surface tension (σ) is an important property when heat transfer involving phase change is analyzed. It affects how well heat transfer surfaces stay wetted, etc. Surface tension has been found to be a linear function of temperature of the form:

σ = a - b•t over some range of temperature (t)

The CRC *Handbook of Chemistry and Physics* (1969) lists surface tension at two temperatures:

@ 11.1°C	23.4 dynes/cm
@ 34.1°C	18.1 dynes/cm

In the range of 0°C to 50°C it could be inferred that the following relationship would apply:

$\sigma = 26.0 - (0.23 \cdot T_c)$ (dynes/cm)

Coefficient of Thermal Expansion (β)

The coefficient of thermal expansion (β) is used when evaluating natural convection situations. It is a measure of how much the volume (or inversely, density) of the fluid changes with each degree change in temperature. A fluid with a high coefficient of thermal expansion will have higher film heat transfer coefficients in natural convection situations. The coefficient can apply both to gases and liquids but ideal gas relationships can generally be used for gas situations. In the case of ammonia liquid, an average value of the coefficient of thermal expansion would be:

$\beta = 3.0 \times 10^{-5}$ (ft^3/°F–lb)

Isothermal Compressibility (K_t)

The isothermal compressibility K_t relates the change in specific volume to the change in pressure at constant temperature. Values for K_t were obtained using the software REFPROP Version 7.0 (NIST 2002) where the ammonia properties are based on Baehr and Tillner-Roth (1994). Values are given in 1/bar for both saturated liquid and vapor as a function of pressure for a few selected values in the following table.

TABLE 2-10
Values for K_t

Press (bar)	Temp (°C)	Liq. Iso. Compressibility, K_t (1/bar)	Vap. Iso. Compressibility, K_t (1/bar)
0.50	-46.517	0.000062755	2.0359
1.00	-33.588	0.000072851	1.0288
10.00	24.895	0.00015795	0.11529
20.00	49.351	0.00024385	0.063791
30.00	65.725	0.00035075	0.047060

The isothermal compressibility is defined mathematically by the equation:

$$K_t = -\frac{\Delta V}{V \Delta P}$$

K_t = Isothermal compressibility

V = Volume of liquid or vapor

ΔP = Pressure change in bar

Heat Transfer Involving Ammonia

Of the three modes of heat transfer (conduction, convection, radiation), it is convective heat transfer that is typically of interest when dealing with ammonia. The key to convective heat transfer involving ammonia is to be able to compare or empirically know the heat transfer film coefficient. These film coefficients are most readily predicted when there is no change of phase taking place.

Most convective heat transfer correlations are based on several dimensionless groups which relate transfer properties of the fluid, in either gaseous or liquid form. These dimensionless groups follow. Note that the properties needed for all of these groups are presented in earlier sections of this chapter.

TABLE 2-11
Dimensionless Numbers Commonly Used in Heat Transfer

Name	Symbol	Value	Application
Nusselt Number	Nu	(hD/k) or (hL/k)	Natural, Forced Convection, Boiling, Condensing
Reynolds Number	Re	(GD/μ) or $(\rho VL/\mu)$	Forced Convection
Prandtl Number	Pr	$\mu c_p/k$	Natural, Forced Convection, Boiling, Condensing
Stanton Number	St	h/Gc_p	Forced Convection
Grashof Number	Gr	$L^3\rho^2 g\Delta T/T\mu^2$	Natural Convection (ideal gases)
		$L^3\rho^2\beta g\Delta T/\mu^2$	Natural Convection

h = heat transfer coefficient

D = diameter

k = thermal conductivity

L = length

G = mass velocity

μ = absolute viscosity

c_p = specific heat

ρ = density

β = coefficient of thermal expansion

T = absolute temperature

g = gravitational acceleration

Free and Forced Convection with Phase Change

Correlations for free and forced convection with phase change occurring are very complex. The reader should consult a heat transfer text or contact a firm which specializes in ammonia evaporators and condensers for assistance. Ammonia exhibits excellent heat transfer properties in phase change situations, which is one of the reasons it is considered an excellent refrigerant.

Research efforts conducted at Ocean Thermal Energy Conversion (OTEC) power plants in the late 70's and early 80's found that ammonia was the most desirable working fluid for the Rankine cycle. As a result of this finding, some interesting work was performed on ammonia evaporators and condensers. Experiments were conducted on conventional plain tube heat exchangers as well as on advanced heat exchangers employing various types of enhanced surfaces. An excellent overview of these results was presented by T. Rabas of Argonne National Laboratory at the 1991 IIAR Annual Meeting in a paper entitled *Energy-Efficiency Comparison of Advanced Ammonia Heat-Exchanger Types* (Rabas 1991). The performance results reported in that paper are briefly summarized:

Ammonia has excellent transport properties. It is also an excellent candidate for surface enhancement because of its large values for surface tension and latent heat.

Values of the ammonia-side film heat transfer coefficient for various evaporator and condenser types were reported.

TABLE 2-12
Film Heat Transfer Coefficients For Selected Applications

Heat Exchanger Description	Film Coefficient (Btu/hr-ft^2-°F)
Evaporators (Unenhanced)	
Plate and Shell — Falling Film — Plain Surface	510
Shell and Tube — Plain Tube — Spray Film	1000
Plate and Frame — Plain Chevron	1010
Evaporators (Enhanced)	
Shell and Tube — Porous Surface Tube — Flooded	4800
Shell and Tube — Porous Surface Tube — Spray Film	4590
Plate and Frame — Porous Surface Chevron	5185
Condensers (Unenhanced)	
Shell and Tube — Plain Tube	1290
Plate and Frame — Plain 60° Chevron	1850
Plate and Frame — Plain 30° Chevron	2590
Condensers (Enhanced)	
Shell and Tube — Horizontal Wire-Wrapped Tubes	5180
Shell and Tube — Vertical-Axial Fluting	8350
Plate and Fin — Serrated Fins	5040

Mass Transfer Involving Ammonia

There are many situations where mass transfer involving ammonia gas or liquid is important. Some mass transfers are directly linked to heat transfer situations involving phase change. There are numerous other mass transfer situations that are not addressed by simple evaporation and condensation processes involving essentially pure ammonia. Several of the more common mass transfer scenarios are discussed herein. *Perry's Chemical Engineers' Handbook* (1997) is a very useful reference for the various modes of mass transfer. The *ASHRAE Handbook of Fundamentals* (2005) also has a simplified summary of mass transfer.

Gas Diffusion

Ammonia gas may be introduced into another gas or vice versa. The rate at which these two gases mix without benefit of any mechanical mixing is governed by Fick's Law of Diffusion. In most practical applications one of the two gases being mixed is very dilute. In those cases the diffusion rate is governed by the equation:

$$m_B = D_{AB} \bullet d\frac{\rho_B}{dy}$$

m_B = mass transfer rate of dilute gas B (mass/time — unit area)

D_{AB} = Diffusivity of gas B in gas A (area/time)

ρ_B = Density of gas B (mass/unit volume)

y = Distance (length)

The density (ρ_B) is directly related to concentration. Concentration can typically be measured fairly readily. The distance (y) between the two points of known concentration is also easily determined. The mass flow of gas B (ammonia in this case) is from the point where concentration is higher to the point where it is lower.

The remaining need is to know the diffusivity (D_{AB}) that governs the diffusion of gases A and B. The literature lists diffusivity of ammonia in air at room conditions:

D_{AB} (Ammonia-Air, @ 77°F, 14.696 psia) = 1.08 ft^2/hr   (ASHRAE 2005)
D_{AB} (Ammonia-Air, @ 25°C, 1 atm) = 0.28 cm^2/sec   (Holman 1972)

For other conditions of temperature and pressure or for ammonia diffusing with other gases, there is an accepted method of computing the diffusivity coefficient (see Perry, 1997):

$$D_{AB} = \frac{0.001T_K^{1.75}\sqrt{\dfrac{1}{M_A} + \dfrac{1}{M_B}}}{P\left(\sqrt[3]{V_A} \quad \sqrt[3]{V_B}\right)^2}$$

T_K = Temperature in K

M_A = Molecular weight of gas A

M_B = Molecular weight of gas B

P = Total pressure, in atmospheres

V_A = Diffusion Volume of gas A

V_B = Diffusion Volume of gas B

The Diffusion Volumes (V) for several common gases are listed in the following table. See *Perry* (1997) for other gases.

TABLE 2-13
Diffusion Volumes for Common Gases

Gas	Diffusion Volume (V)
Hydrogen	7.07
Helium	2.88
Nitrogen	17.90
Carbon Monoxide	18.9
Oxygen	16.60
Nitrogen Dioxide	35.9
Carbon Dioxide	26.90
Ammonia	14.90
Water Vapor	12.70
Air	20.10

Gas Absorption in an Ammonia-Air-Water System

Removal of ammonia gas from an air stream is a mass transfer situation that has been studied extensively over the years. *Perry's Chemical Engineers' Handbook* (1997) addresses the subject and shows four figures that are related specifically to ammonia-air-water absorption systems where ammonia is absorbed from an air stream in a water spray/packed column device. Perry also mentions several references which provide even greater detail about the subject.

The book *Absorption and Extraction* (Sherwood 1937) contains extensive information concerning absorption of ammonia by water in packed towers, by liquid spheres, in spray towers, and in wetted wall towers.

The paper *Performance of Drip-Point Grid Tower Packings: III. Gas-Film Mass Transfer Coefficients; Additional Liquid-Film Mass Transfer Coefficients* by Molstad, McKinney, and Abbey (1943) reports on a myriad of tests of absorption of ammonia in water. The resultant gas phase mass transfer coefficients for various packings at different gas and liquid flow rates are presented.

A follow-up paper *IV. Additional Gas-Film Mass Transfer Coefficients* by Parsly, Molstad, Cress, and Bauer (1950) reports on additional tests of the rate of ammonia absorption in water.

Absorption of ammonia gas by a water spray in a chamber without packing media was studied by D. Fenton in ASHRAE-sponsored research at Kansas State University. His paper *Absorption of Ammonia into Water* (1991) addresses the theory and some actual results from field testing. The testing showed that a simple fog nozzle spraying downward against the flow of ammonia gas was 85% effective at absorbing ammonia gas when sprayed at a ratio of two gallons of water per pound of ammonia.

Indications are that by checking these above references, in addition to the references they cite, there is little in the area of ammonia gas absorption in water that has not been thoroughly tested.

Evaporation of Liquid Ammonia Into Air

Inadvertent spills of liquid ammonia can result in pools of pure liquid ammonia or aqueous ammonia being exposed to the atmosphere. The rate of ammonia evaporation to the air may be of interest for emergency response planning and/or modeling needed for process hazard management activities.

When a quantity of liquid ammonia is released into an open container or into a pool on the ground, its behavior will be a function of its temperature prior to release, how readily the liquid can absorb heat from its surroundings, the amount of free surface for evaporation, extent of movement of air over the surface, etc.

The warmer the liquid prior to release, the greater the amount that will flash to vapor immediately upon release. If no air were present, the liquid would cool very quickly to approach –28°F which is the saturation temperature at atmospheric pressure. However, because air is present, the partial pressure of the ammonia is significantly less than atmospheric pressure. As a result, the liquid will cool to a temperature well below –28°F. The final temperature will be a function of heat transfer from the container walls or ground, the sensible heating effect of the warmer air, and the cooling effect resulting from evaporation of ammonia at the air interface.

The U.S. EPA has provided an equation (EPA 1987) which can be used to predict the evaporation rate of ammonia from a 1 cm deep pool of liquid. The equation has been modified to use IP units and to be based on one square foot of pool surface:

$$\frac{QR}{A} = \frac{0.0597u^{0.78}\,VP}{T_R}$$

$\dfrac{QR}{A}$ = Evaporation rate (lb/min –ft^2)

u = Wind speed (miles/hour)
VP = Vapor pressure at temperature of liquid (psia)
T_R = Absolute temperature of liquid (degrees Rankine)

Evaporation rates have been calculated for several different liquid temperatures and at two different wind speeds. The results show that evaporation rates are strongly influenced by both the liquid temperature and the wind speed.

TABLE 2-14
Calculated Evaporation Rates (lb/min-ft^2)

Liquid Temperature	Wind Speed	
	5 mph	15 mph
–50°F	0.004	0.009
0°F	0.014	0.033
50°F	0.037	0.086
100°F	0.079	0.186

Note that if warm liquid is spilled, the initial rate of evaporation will be quite high. As the evaporation process cools the remaining liquid, the evaporation rate will decrease. Deeper pools will not cool as rapidly, maintaining a higher evaporation rate.

The rate of evaporation of ammonia from an open pool or container can be greatly reduced by covering the surface with a tarpaulin suitable for very low temperature. If the outer edges of the tarpaulin can be sealed to the container or to the ground the evaporation can essentially be stopped. Another method of reducing the evaporation rate by as much as 80% is to apply a special alkaline-compatible foam to the surface.

Frictional Losses (Momentum Transfer) for Ammonia

Ammonia gas and liquid are commonly transported within closed piping systems. It is necessary to be able to calculate the friction losses experienced by the gas or liquid as it passes through a piping system. Friction loss calculations allow pumps and piping to be properly designed.

Several charts and tables have been developed for the ammonia refrigeration industry. These tools cover the situations most commonly encountered in refrigeration applications but do not provide the basic correlations from which the specific data was developed. These correlations are particularly useful if one is interested in computer-aided design and analysis of piping systems. Simplified algebraic expressions for pressure loss can be developed for vapor and liquid in typically encountered Reynolds Number ranges for steel pipe. Such expressions are derived in the following section of this chapter. Because of the complexity of the expressions, users should verify and test the expressions for accuracy with available charts or tables prior to general use.

Derivation of Simplified Pressure Loss Expressions

Perry (1997) provides the Fanning or Darcy equation for steady flow in full pipes under isothermal conditions as follows:

$$F = \left(\frac{4\,fL}{D} \right) \frac{V^2}{2g_c} = \frac{32\,fLq^2}{\pi^2\,g_c D^5}$$

Rearranging the equation, we can arrive at an expression for pressure loss per 100 feet of pipe which is a commonly used measure for pressure loss:

$$\frac{\Delta p}{100\text{ft}} = \frac{3200 f q^2 \rho}{\pi^2 g_c D^5}$$

Δp = pressure loss (pound per square foot)

f = friction factor (dimensionless)

q = volume flow rate of fluid (ft^3/sec)

g_c = gravitational constant (32.2 lb$_m$ - ft/lb$_m$ - sec^2)

D = diameter (feet)

ρ = fluid density (lb/ft^3)

Volume flow rates can be expressed in terms of mass flow rate G (lb/sec) and density (ρ) as follows:

$$q = \frac{G}{\rho}$$

Vapor

The density of ammonia vapor can be reasonably approximated by the expression:

$$\rho = \frac{P}{0.6\,(T_F + 460)}$$

P = absolute pressure (psia)

T_F = temperature (degrees F)

Combining all of the above expressions results in the following:

$$\frac{\Delta p}{100\,ft} = \frac{6.05\,fG^2\,(T_F + 460)}{D^5 P}$$

For very precise calculations the friction factor f needs to be determined by looking at a Moody chart, which is a plot of friction factor vs. Reynolds number and relative roughness of the pipe material. A Moody chart can be found in Perry's or any one of a number of other references. However, Perry also suggests a relationship for f which is a relatively simple function of the Reynolds number for turbulent flow (1997). It results in a reasonable approximation of the friction factor for ordinary steel pipe. The expression is as follows:

$$f = \frac{0.014}{Re^{0.16}}$$

which is valid over the Reynolds (Re) number range: 3×10^3 to 3×10^8 and relative roughness ($\varepsilon\,/\,D$) range: 10^{-6} to 10^{-2}. The pipe's surface roughness is ε and the inside pipe diameter is D. The ratio ($\varepsilon\,/\,D$) is dimensionless. The Reynolds number, also dimensionless, is defined as follows:

$$Re = \frac{DV\rho}{\mu}$$

The viscosity of the vapor (μ) can be approximated by the expression:

$$\mu = 0.024 + \frac{T_F}{18000}\left(\frac{lb_m}{ft - hr}\right)$$

Velocity can be represented by the expression:

$$V = \frac{4G}{\pi D^2}$$

Using these expressions, f can be calculated as follows:

$$f = \frac{0.014}{\left\{\dfrac{4575 g_c}{\left[D\left(0.024 + \dfrac{T_F}{18000}\right)\right]}\right\}^{0.16}}$$

Combining equations, the resultant expression for pressure loss of ammonia vapor in turbulent flow is as follows:

$$\frac{\Delta p}{100 \ ft} = \frac{73.29 W^{1.84} \ (T_F + 460) \ \left(0.024 + \dfrac{T_F}{18000} \right)^{0.16}}{D^{4.84} \ P}$$

W = mass flow (lb/sec)

T_F = temperature (degrees F)

D = diameter (inches)

P = pressure (psia)

This expression will normally result in pressure losses which are 10–20% higher than will be obtained if the solution is determined precisely. The IIAR Piping Handbook presents calculation methods that are more accurate than the above procedure and also accommodate a wider range of application (IIAR 1999).

Liquid

A derivation approach similar to that for ammonia vapor can be performed for ammonia liquid:

$$\rho = 41.34 - (0.049 T_F) \ \left(\frac{lb}{ft^3} \right)$$

The viscosity of ammonia liquid can be expressed as a function of temperature:

$$\mu = 0.56 - \frac{T_F}{400} \ \left(\frac{lb_m}{ft–hr} \right)$$

Combining the above equations, the following expression is obtained for pressure loss of ammonia liquid in turbulent flow:

$$\frac{\Delta p}{100 \ ft} = \frac{121.4 W^{1.84} \ \left(0.56 - \dfrac{T_F}{400} \right)^{0.16}}{D^{4.84} \ (41.34 - (0.049 T_F))}$$

W = mass flow (lb/sec)

T_F = temperature (degrees F)

D = diameter (inches)

This expression yields results which are very close to those obtained by precise solution.

If the reader uses either of these two simplified expressions on either a programmable calculator or a computer, programming errors can be detected by running the following test cases:

Test Case 1   Ammonia vapor

T_F = 20°F

P   = 45 psia

W = 2 lb/sec

D = 4.026"

Δp/100 ft = 1.83

Test Case 2   Ammonia liquid

T_F = 90°F

W = 20 lb/sec

D = 3.068"

Δp/100 ft = 3.01

Two Phase Flow   When pipes carry both ammonia liquid and vapor simultaneously, the above pressure drop correlations do not apply directly. The gas relationship is used but with a multiplier which is based on the mass fraction, volume fraction, and viscosity fraction of each phase. For further information, refer to a paper by Chawla and Thome, *Total Pressure Drop of Refrigerants Flowing Through Evaporator Tubes* published in *Kaltetechnik-Klimatisiering*, No. 10, 1967, p. 306–309. Also refer to the paper *Pressure Drop in Two Phase Flow* presented by P. Jacobsen at the IIAR 1991 Annual Meeting.

Catastrophic Release of Pressurized Ammonia   Emergency response planning for catastrophic releases of pressurized ammonia requires that a special type of momentum transfer be addressed. Because ammonia can be stored as a gas, saturated gas/liquid, or subcooled liquid, several different types of flow regimes can occur when a tank, nozzle, or pipe ruptures. For further information, refer to the *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs* (AIChE 1994). Also refer to *Desert Tortoise Series Data Report — 1983 Pressurized Ammonia Spills* (Goldwire et al. 1985).

Aqueous Solution Properties

Although the primary subject of this Data Book is anhydrous ammonia, it is deemed appropriate to also address the subject of aqueous solutions. Perhaps the most common human exposure to ammonia is by way of weak (2–5%) aqueous solutions used for household cleaning.

Aqueous ammonia solutions are correctly referred to as ammonium hydroxide solutions but are also referred to as aqua ammonia or water-ammonia. The solubility of ammonia in water is strongly affected by the solution temperature, with decreased solubility at higher temperatures. Refer to Figure 2-8 for a chart of solubility vs. temperature.

FIGURE 2-8 Solubility of Ammonia in Water
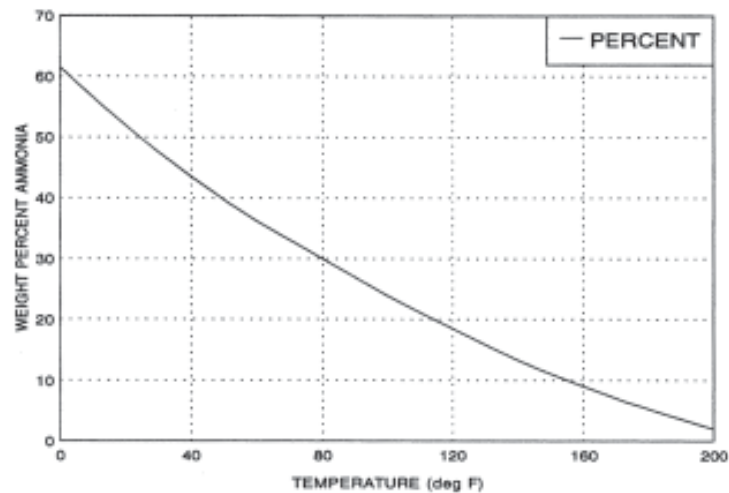
Recent ASHRAE sponsored research was conducted by Fenton et al. (1991) which studied and then tested the mixing process involving liquid ammonia and water. The paper *Absorption of Ammonia into Water* (Fenton et al. 1991) presents good information about the formation of aqueous ammonia solutions.

Concentrative Properties of Aqueous Ammonia (Ammonium Hydroxide) solutions are provided in Table 2-15. Additional information can be found in the *CRC Handbook of Chemistry and Physics* (1969).

TABLE 2-15
Concentrative Properties of Ammonium Hydroxide Solutions

WT %	NH₃%	S.G.	g/l	M	#/GAL	I.R.	FP°C	FP° F
0.00	0.00	1.000	0.0	0.000	0.00	1.333	0.0	32.0
5.00	2.43	0.989	49.4	1.409	0.20	1.334	-3.2	26.2
10.00	4.86	0.979	97.8	2.789	0.40	1.335	-6.0	20.8
15.00	7.29	0.970	145.2	4.142	0.59	1.337	-9.6	14.6
20.00	9.72	0.960	191.7	5.470	0.78	1.338	-14.4	6.06
30.00	14.58	0.943	282.3	8.055	1.14	1.341	-28.9	-20.0
40.00	19.44	0.926	369.9	10.55	1.50	1.344	-54.7	-66.4

The table columns are:

WT % = Weight percent of ammonium hydroxide

NH₃ % = Weight percent of anhydrous ammonia

S.G. = Specific gravity of solution at 20°C

g/l = Grams of ammonium hydroxide per liter of solution

M = Molar concentration of ammonium hydroxide in g-moles/liter
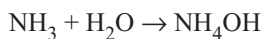
#/GAL = The weight of ammonia per gallon of solution

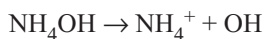I.R. = Index of refraction at 20°C relative to air, for sodium yellow light

FP°C = Freezing point in Celsius

FP°F = Freezing point in Fahrenheit

When ammonia is dissolved in water the theoretical reaction is as follows:

$NH_3 + H_2O \rightarrow NH_4OH$

However, it is known that dissociation takes place:

$NH_4OH \rightarrow NH_4^+ + OH$

(There is also some evidence that some ammonia exists in solution in the form of

$NH_3 \cdot H_2O$ and $NH_3 \cdot 2H_2O$.)

The dissociation constants of aqueous ammonia solutions in the temperature range of 0 to 50°C are as follows (CRC 1969):

TABLE 2-16
Dissociation Constants

Temperature °C	pK_b	K_b
0	4.862	1.374×10^{-5}
10	4.804	1.570×10^{-5}
20	4.767	1.710×10^{-5}
30	4.740	1.820×10^{-5}
40	4.730	1.862×10^{-5}
50	4.723	1.892×10^{-5}

These constants can be used to calculate the extent of dissociation of the ammonium hydroxide molecules.

Ammonia is considered a weak base and ionizes in water much less than a strong base such as sodium hydroxide. A molar solution of ammonia has an hydroxyl ion concentration of about 2 percent of that in a molar sodium hydroxide solution.

Hydroxyl ion (and hydrogen ion) concentration is measured by pH. As ammonia is dissolved in water the pH elevates rapidly and then flattens out in the pH = 12 range. Figure 2-9 shows the logarithmic relationship between pH and concentration expressed as normality.

FIGURE 2-9 Ammonium Hydroxide Solution pH (70 deg. F)
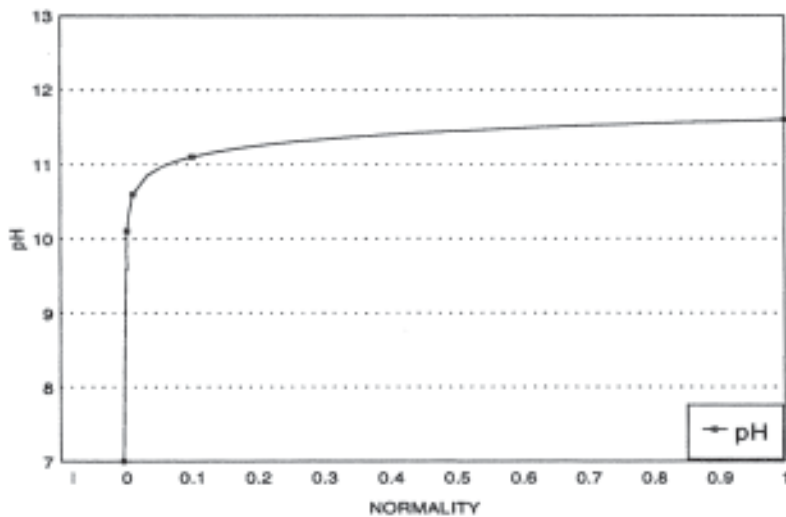
1 Normal=17.03 grams/liter

Corbitt's *Standard Handbook of Environmental Engineering* (1990) shows a graph demonstrating the influence of pH and temperature on the relative presence of ammonium and unionized ammonia in water solutions. The graph is reproduced as Figure 2-10.

FIGURE 2-10 Influence of pH and Temperature
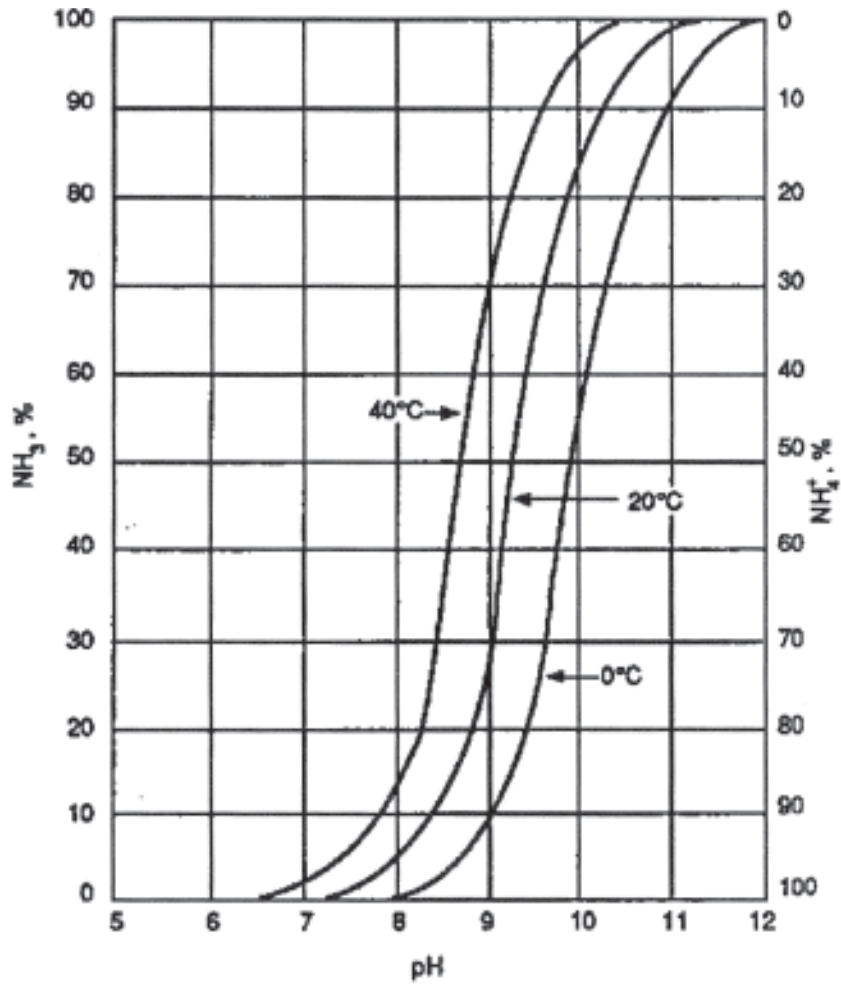
Reproduced with permission of The McGraw-Hill Companies.

It is sometimes necessary to know the surface tension of a solution. Following is a brief table of surface tension of ammonium hydroxide at 18°C as a function of the weight percent of ammonium hydroxide in the solution.

TABLE 2-17
Surface Tension of Ammonium Hydroxide

NH$_4$OH Concentration	Surface Tension (Dynes/cm)
1.72	71.65
3.39	70.65
4.99	69.95
9.51	67.85
17.37	65.25
34.47	61.05
54.37	57.05

When gaseous ammonia or liquid ammonia is dissolved in water to form an aqueous solution there is liberation of heat from the exothermic reaction which takes place. More temperature rise occurs when the ammonia is dissolved from the gaseous form than when it is dissolved from the liquid form. This is consistent with the higher energy level of the gaseous ammonia. Heats of solution for gas and liquid are reported to be (CRC 1969):

Gas   -771 Btu/lb [-7290 cal/g-mole]
Liquid   -348 Btu/lb [-3290 cal/g-mole]

An aqueous solution of ammonia exerts a total vapor pressure at its surface which is comprised of the partial pressure of the water and the partial pressure of the ammonia. *Perry's Chemical Engineers' Handbook* (1997) contains extensive tables of both partial pressures and the total vapor pressure. Some selected conditions of solution temperature and ammonia concentration are shown in Table 2-18.

TABLE 2-18
Vapor Pressure of Ammonium Hydroxide (psia)

TEMP	NH$_3$ %	H$_2$0 V.P.	NH$_3$ V.P.	TOT V.P.
40°F	4.74	0.115	0.33	0.45
40°F	9.50	0.108	0.66	0.77
40°F	19.10	0.095	1.92	2.01
40°F	28.81	0.083	5.13	5.21
80°F	4.74	0.48	1.04	1.52
80°F	9.50	0.45	1.98	2.43
80°F	19.10	0.40	5.45	5.85
80°F	28.81	0.34	13.52	13.86
120°F	4.74	1.60	2.67	4.27
120°F	9.50	1.51	4.95	6.46
120°F	19.10	1.33	13.09	14.42
120°F	28.81	1.15	30.54	31.69

Following are some selected values of specific heat for aqueous ammonia solutions as given in *Perry's Chemical Engineers' Handbook* (1997).

TABLE 2-19
Specific Heat of Aqueous Ammonia Solutions

MOLE % NH$_3$	2.4°C	20.6°C	41.0°C	61.0°C
0.0	1.01	1.00	0.995	1.00
10.5	0.98	0.995	1.06	1.02
20.9	0.96	0.99	1.03	N/A
31.2	0.956	1.00	N/A	N/A
41.4	0.985	N/A	N/A	N/A

Note: Units are cal/g–°C or Btu/lb–°F

The viscosity of aqueous ammonia solutions is higher than for pure liquid ammonia. Table 2-20 contains viscosity data for 26% concentration aqueous ammonia as obtained from *Perry's Chemical Engineers' Handbook* (1997).

TABLE 2-20
Viscosity of Aqueous Ammonia Solutions at 26% Concentration

Temperature	Centipoise
–40°F [–40°C]	5.0
0°F [–18°C]	2.8
40°F [4°C]	1.7
80°F [27°C]	1.1
120°F [49°C]	0.7

As concentration varies between 0% and 100% the viscosity varies from that of pure water to that of pure ammonia.

The diffusivity of ammonia in water is reported to be in the range of 1.7 to 2.3 x 10^5 cm^2/sec at 25°C (Perry 1997). The effect of temperature is such that the diffusivity-viscosity product divided by absolute temperature is a constant.

An excellent source of information on ammonia-water mixtures is the Institute of Gas Technology's *Bulletin No. 34, Physical and Thermodynamic Properties of Ammonia-Water Mixtures* (1964).

There are also three references which have equations of state for ammonia-water mixtures:

• *Equations of State for the System Ammonia-Water for use with Computers* by S. Schulz (1971) presented at the XIII International Congress of Refrigeration, Vol. 2.

• *Equation of State for Ammonia-Water Mixtures* by Ziegler and Trepp, published in the *International Journal of Refrigeration* in March of 1984.

• *NH$_3$-H$_2$O (ammonia-water) — Thermophysical Properties of Refrigerants* edited by the International Institute of Refrigeration, Paris, France, 1993.