

UNDERSTANDING HYDRAULIC SHOCK

In the last issue of the **COLD FRONT (VOL. 8 NO. 4)** we reviewed basic processes and equipment involved with hot-gas defrosting air-cooling evaporators. In this article, we focus on causes, risks, and cures of hydraulic shock in refrigeration systems. Defrost is one of the potential areas where hydraulic shock can occur.

INTRODUCTION

Hydraulic shock is defined as the “internal pressure stress imposed in piping systems by a sudden change in liquid velocity, as by the sudden stopping of flow” (ASHRAE 1991). Hydraulic shock is sometimes referred to as “hydraulic hammer” or “water hammer.” When a moving liquid is rapidly stopped or decelerated, the rise in pressure can generate substantial force. In the best case scenario, the forces caused by hydraulic shock are low and not readily obvious by direct observation. In moderate cases, hydraulic shock generate higher pressures as evidenced by observing pipes moving and by audible “knocking.” In extreme cases, hydraulic shocks will generate

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extremely high pressures which can cause the catastrophic failure of valves, piping, evaporator coils, and other equipment.

Within refrigeration systems, hydraulic shock can occur in a number of locations:

- Liquid (saturated & subcooled) supply lines with large liquid feed solenoid valves
- Recirculated liquid return (wet suction) mains & branches
- Defrost condensate return lines
- Hot gas mains & branches
- Evaporator suction headers (when evaporators are defrosted with top-fed hot-gas)
- Transfer system return lines

The hydraulic shock in liquid lines is identical to water hammer that occurs in hydronic systems. The hydraulic shock events that create the highest pressures often occur in situations where vapor and liquid ammonia are found together with an internal disturbance (non-equilibrium). One disturbance mechanism is initiated by the large volume change that occurs when ammonia vapor condenses by contact with subcooled liquid. The hydraulic shock created by this triggering mechanism is sometimes referred to as “condensation-induced hydraulic shock” (CIS). Another type of disturbance that can create hydraulic shock is the entrainment and rapid acceleration of liquid in a fully- (trapped) or partially-filled section of pipe or component when a large vapor flow is introduced upstream. Referred to as a “vapor-propelled liquid slug (VPLS),” the

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NOTEWORTHY

- The webcourse **ENGINEERING SAFETY RELIEF SYSTEMS** was scheduled for **December 14-18, 2009**. See more information [here](#).
- Send items of note for next newsletter to **TODD JEKEL**, tbjekel@wisc.edu.

pressures developed by this form of hydraulic shock can be significant and overt signs of CIS include loud banging of piping, valves, and fittings. Regardless of how it develops, hydraulic shock can lead to the catastrophic failure of piping, valves, and other equipment (Loyko, 1989; Glennon & Cole, 1997; Wiencke, 2008). The pressures developed during hydraulic hammer were experimentally measured on the order of 500 psig [34.5 barg] (Martin, 2007) and theoretically estimated up to 11,000 psig [760 barg] (Shelton & Jacobi, 1997b).

DECELERATION OF LIQUID FLOW

The Joukowski equation (Joukowski, 1904; Haested Methods, 2003) is a simplified form that can be used to estimate the pressure excursion attributable to the rapid deceleration of a flowing liquid. The Joukowski equation is given by:

$$\Delta p = -\rho a \Delta V$$

where Δp is the pressure rise over the normal pressure, ρ is the fluid density, ΔV is the change in velocity, and a is the actual speed of sound in the piping given as follows:

$$a = \frac{c}{\sqrt{1 + \frac{d}{t} \cdot \frac{K}{E}}}$$

Where c is the speed of sound of the fluid, d is the internal diameter of the pipe, t is the pipe thickness, K is the bulk modulus of the fluid, and E is the modulus of elasticity for the pipe material. [Note: if you use IP units (ft,s,lb), the right-hand side of the equation must be divided by 144 in²/ft² and 32.2 lb·ft/s²-lb_f to get pressure in psi.]

Consider a 25 ton [88 kW_T] evaporator configured as follows:

- Liquid supply is -30°F [-22°C] at 12 psig [0.83 barg]
- Liquid feed solenoid ¾" [1.9 cm]
- Liquid recirculation rate at 4:1
- Liquid feed piping is ¾" NPS [1.9 cm] schedule 80
- Full-load refrigerant mass flow rate is 33.9 lb/min [0.256 kg/s] resulting in a an average pipe liquid velocity of 132.3 ft/min [0.67 m/s]

Using the Joukowski equation, an instantaneously closed solenoid could theoretically generate a 116 psi [7.9 bar] rise in pressure. For a more realistic 20 ft [6.1 m] branch line, the pressure rise is approximated by the following (Avallone et al., 2007):

$$\Delta p \approx -\rho \Delta V \left(\frac{L}{t_c} \right)$$

Where L is the length of the pipe and t_c is the closing time of the valve. If the closing time of the pilot-operated solenoid is 0.5 s, this would result in a pressure rise of only 0.8 psi [0.056 bar].

Liquid makeup lines from the high pressure receiver can have larger pressure excursions from hydraulic hammer because they generally have higher velocities. Liquid line design velocity ranges are in the 200 ft/min to 270 ft/min range [1-1.36 m/s] (IIAR 2004). The higher velocity results in a larger operating pressure drop across the valve and a faster closing response time leading to higher pressure excursions. For a 30 ft [4.6 m] long 1-½" [3.8 cm] Schedule 80 pipe with liquid velocity at 230 ft/min [1.17 m/s] and a pilot-operated solenoid valve closing within 0.05 s, an approximate pressure rise of 18.5 psi [1.3 bar] results. To put this case into perspective, this velocity and pipe size corresponds to liquid makeup requirements for a 500 ton [1,760 kW_t] load. The instantaneously closing valve would theoretically create a 130 psi [9 bar] pressure rise upstream of the valve.

These examples illustrate the potential to develop moderate pressure increases from hydraulic shock events. For each example, the resultant pressure rise due to the **instantaneous** closing of a solenoid can generate more than 110 psi [7.6 bar]. Fortunately for designers and owners, the combination of ammonia's low required liquid flow rates (due to its large heat of vaporization) and minimum piping size of ¾" [1.9 cm] result in low velocities in liquid feed piping and subsequently pressure rises less than the design pressure of the piping system.

Does this mean that we never experience hammering of liquid piping? Not necessarily. Improperly set (i.e. too far open) hand-expansion or metering valves lead to larger velocities with the potential for higher developed pressures during the closure of downstream liquid feed solenoid valves. Consider that if the setting of the hand-expansion valve in the liquid makeup example caused the liquid feed solenoid to be open only 25% of the time, the resultant pressure rise for the cycling of the liquid feed solenoid would be >50 psi [3.4 bar].

Another situation that creates an opportunity for hydraulic hammering to occur is evaporator configurations with a significant amount of piping between the liquid feed solenoid and the metering valve for overfed evaporators (Glennon & Cole, 1997). When the liquid-feed solenoid is closed, the liquid residing between the solenoid and the expansion valve can be "pumped out" by the evaporator. When the evaporator subsequently calls for make-up liquid, it rapidly enters the vapor-filled piping (which is at evaporating pressure) causing the metering valve or downstream fittings to be hammered. To minimize the likelihood of this form of hammering, one valve manufacturer recommends limiting the length of piping between the solenoid & the hand-expansion valve to 2 ft [0.6 m] or less (Hansen, 2000).

Glennon & Cole (1997) also explore a situation where a hydraulic shock was caused by the pump discharge pressure transient when a large evaporator called for liquid during start-up after defrosting/cleaning. In this case, the liquid refrigerant pump was dedicated to the spiral freezer evaporators; therefore, during start-up the pump was at its minimum flow/maximum discharge pressure condition. When the solenoid opened, the flow through the valve was very high due to the large pressure drop across the solenoid. The shock started between the solenoid and hand-expansion valve, but a reflected shock and subsequent movement was seen at the pump discharge check as well. The pipe movement lasted approximately 20 s.

If you see liquid piping moving as the solenoid cycles, you should investigate the problem further. Causes may be as simple as a metering valve (hand-expansion) being too many turns open or piping supports that have failed. The origin of the piping movement may be more complicated such as an undersized section of piping. Either way, the root cause should be determined and changes evaluated

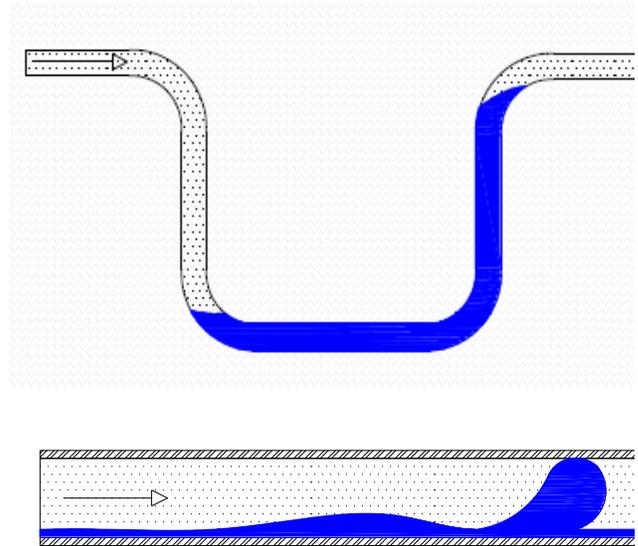
to prevent the problem. For systems with large load variations (e.g. pull down) and a single hand-expansion valve, a potential change to eliminate hydraulic shock events during low loads is the application of a motorized expansion valve for liquid makeup to the vessel (or evaporator). The use of a modulating type valve allows a more continuous feed of liquid and less fluctuation in flow caused by solenoid cycling. An alternate solution is the installation of two (2) feed valve trains (solenoid and hand-expansion valve) in parallel with only one liquid feed valve train operating for "normal" (i.e. non-pull down) operation and both of the operating for the pull-down load (Loyko, 1992).

ACCELERATION OF LIQUID SLUG

In relative terms, the magnitude of hydraulic hammering of liquid-filled piping is low to moderate. Moderate and high levels of hydraulic shock can occur in piping systems when vapor and liquid are present. The hydraulic shock and hammer that occurs in these sections of piping are among the most severe. There are two (2) distinct ways of forming shocks in two-phase (liquid and vapor) piping (Shelton & Jacobi, 1997a): mechanical & thermodynamic. The mechanical form is called a *vapor-propelled liquid slug* (VPLS) and usually arises when a rapid rush of vapor flow is initiated (such as from the opening of a large valve with a high pressure upstream vapor). The thermodynamic form is called *condensation-induced shock* (CIS) and arises from the large reduction in volume of vapor that condenses due to heat transfer between the refrigerant vapor in the presence of subcooled liquid. VPLS and CIS can work together during a hydraulic shock event.

VAPOR-PROPELLED LIQUID SLUG (VPLS)

Slugs of liquid can form two (2) ways (Shelton & Jacobi, 1997a): statically shown below as a liquid slug formed by a piping trap, or dynamically shown below as a wave formed by vapor flow over a partially filled liquid pipe that completely encompasses the pipe cross section.



A recent ASHRAE research project showed that a VPLS could consistently be generated in a 6" [15 cm] section of piping with as little as 1-½" [3.8 cm] of liquid ammonia lying in the bottom of the pipe section (Martin 2007). The peak pressures measured at the end cap of the test section were as high as 500 psig [34.5 barg] during some of the experiments. In a more theoretical analysis of the problem, Shelton & Jacobi (1997b) calculated that VPLS required piping to be at least 35% full of liquid and peak pressures were estimated to be >11,000 psig [760 barg]. Regardless of the details, both of these studies indicate that segments of piping that are partially filled with liquid are still capable of enabling hydraulic shocks and highlight the importance of proper pitching and draining of two-phase piping. To help facilitate the draining of liquid refrigerant in horizontal segments of piping systems, one valve manufacturer recommends that globe valves be installed with stems at the 3:00 or 9:00 o'clock position to permit a more free flow of liquid through the valve (Hansen 2003). Minimizing the liquid hold-up upstream of isolation valves is especially important in two-phase lines.

Another factor that underscores the magnitude of pressures that can be developed in VPLS events is due to the fact that the velocities

capable of being developed are much higher than those outlined earlier in the discussion of liquid-only hydraulic shock. When this fast moving, liquid slug encounters an obstruction (valve, elbow or end cap) the slug will rapidly decelerate and cause a force that announces its arrival in a loud “bang” of the piping system. The banging may be audible, physical or both. Banging or moving piping should be investigated immediately to determine the root cause and mitigate its occurrence and prevent the potential catastrophic failure that can occur through repeated shock events.

The root cause of a VPLS event is often the quick opening of a large valve with a high operating pressure differential. Two examples of this situation include: at initiation of a hot-gas feed to a large coil during a defrost cycle and the termination of the hot-gas defrost cycle. The severity of the hydraulic shock potential increases for larger capacity and lower operating temperature evaporators. The hydraulic shock created by a rapid inrush of hot-gas from the opening of a large solenoid valve can cause failures in the header sections of the evaporator unit. Upon termination of the defrost cycle and the rapid opening of the stop valve to suction when the coil is pressurized, failure to the suction stop valve or downstream wet suction piping can occur. The risk of failure can be minimized by the use of proper coil bleed times and suction stop valve selections (e.g. avoiding the use of quick-opening suction stop valves).

Wiencke (2008) investigated a hydraulic-shock failure of an evaporator header that occurred at the initiation of a defrost cycle. Finite element analysis of the header manifold suggested that pressures causing the catastrophic failure were in excess of 2,500 psig [172 barg]. Wiencke’s analysis showed that the resultant vapor velocity required for this pressure excursion could be generated by the opening of the main hot-gas solenoid on the evaporator without sufficient soft-gas. For more details on proper sequences of defrost including principles of soft-gas and bleed, refer to the **COLD FRONT (VOL. 8 No. 4)**.

Below is a picture of a new (<6 month old) system that failed due to a hydraulic shock event. The shock was caused when the suction stop valve on a large, low-temperature evaporator was opened without a more gradual depressurization of the evaporator using a proper bleed period. Although appropriate defrost controls were implemented in the automatic operation of this unit, they were bypassed by operations staff. While not known definitively, it is likely that the reason that the failure occurred at the weld and not at the obstruction was due to a “notch” at a weld that was not fully penetrated.



There are multiple issues with hot-gas defrosting evaporators that can exacerbate hydraulic shocking or hammering:

- **Design Issues**
 - No soft-gas
 - No bleed
 - Use of rapid opening large suction stop valves (CK-2, HCK-2, or HS9B)
 - Liquid trap between the evaporator & wet-suction return piping
 - Wet-suction piping that doesn't adequately drain back (i.e. traps liquid) to the recirculator or suction trap
 - Notches (lack of full penetration welds) that can act as a stress concentration points with subsequent failure
- **Operational issues**
 - Inadequate pump out time prior to defrost initiation
 - Inadequate soft-gas time
 - Inadequate bleed time
 - Interruption of defrost cycle prior leading to opening of the suction stop valve with no bleed
- **Maintenance**
 - Failed soft-gas solenoid
 - Failed bleed solenoid

Any one of these may be sufficient to lead to hydraulic shocks. To minimize the likelihood of a shock, all of these areas should considered and appropriate preventive steps taken.

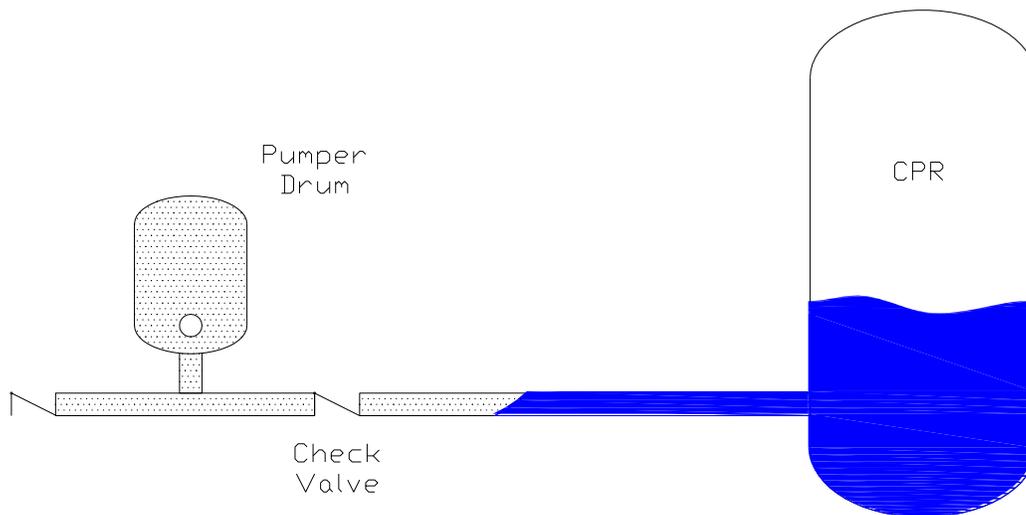
CONDENSATION-INDUCED SHOCK

Loyko (1992) explored condensation-induced hydraulic shock in detail. CIS can occur when vapor and subcooled liquid are present together. The driving force for this type of shock is the heat transfer between the warm vapor and cold liquid and the resultant large reduction in volume that occurs as vapor ammonia condenses to a liquid. Consider the volume ratio (vapor liquid / volume vapor) of ammonia for a range of saturation conditions below. This table illustrates that at -40°F [-40°C] condensed liquid takes up less than 0.1% of the volume of the vapor!

Saturation Temp. [°F] (°C)	Volume ratio of liquid to vapor
-40 (-40)	0.0009
0 (-17.8)	0.0026
+40 (+4.4)	0.0064

This reduction in volume will create a “vacuum” that encourages an inrush of volume from elsewhere in the system. If the volume that fills the void is liquid, the result will be a hydraulic hammer event at an obstruction.

The most common location for this type of shock is on gas-driven transfer systems (primarily in systems with controlled pressure receivers). The below figure illustrates a trapped liquid bubble between the check valve downstream of the pumper drum and the CPR. It is typical for the liquid transfer line to be connected below the liquid level in the CPR in order to provide the coldest liquid back to the plant. Unfortunately, this configuration insures that the volume flowing back to fill the vacuum pocket when the trapped bubble collapses will be liquid from the CPR. The result will be a shock and hammer event that has the potential to cause a catastrophic failure of the check valve or connected piping.



As with VPLS, there are multiple issues with transfer systems that can exacerbate shocking or hammering:

- **Design Issues**
 - No regulation of the supply gas pressure for transfer back to controlled pressure receiver (consider implementing an outlet pressure regulator upstream of the pumper drum)
 - The use of timers for termination of the transfer cycle (consider using floats or another form of level sensing to terminate the transfer cycle or an alternative design that uses a pump rather than gas pressure for the transfer)
- **Operational issues**
 - Improper adjustment of timer settings causing the complete draining of liquid from the pumper drum (consider requiring supervisor approval prior to change if possible)
- **Maintenance**
 - Proper maintenance on the three-way valve and controls are critical
 - Monitoring cycles on the pumper drum to help guide maintenance frequency on check valves, three way valve and controls

CONCLUSIONS

Repeated examples of failures due to the pressures and forces created by hydraulic shocks leave no doubt of the seriousness of these events. They continue to happen today despite early warning signs of audible banging and visible shaking of piping systems that occurs in systems.

CALL TO ACTION

The information in the article is worthless unless it prompts you to evaluate areas within your system that are prone to hydraulic shock. Don't believe that a catastrophic failure due to hydraulic hammer cannot occur in your system.

If you have large (>20 tons [53 kW_t]), low-temperature (<-15°F [-26°C]) evaporators in your plant, put the following on your "to-do" list **TODAY**:

- Evaluate suction and hot-gas piping - looking for liquid traps that can create a liquid slug.
- Check your evaporator defrost sequence times to ensure that there is adequate pump out and bleed times.
- Make sure that the soft-gas and bleed solenoids are operational. Make sure that they both have their preventive maintenance up-to-date per the manufacturer's recommendations.
- Actually observe/monitor the beginning and end of a defrost cycle for EACH evaporator in your plant. Is there noticeable banging of valves or shaking of piping? If so, consider implementing (or adjusting the timing of) soft gas or bleed cycles as appropriate.

In addition, check your transfer system operation to assure that the pumper drum does not completely empty its contents past the downstream check valve.

Hot gas mains and branches should be checked to insure that they are properly pitched and drained to keep them as free from condensed liquid as possible. If they can hold up liquid, consider installing liquid drainers to keep them dry.

And lastly, monitor your larger liquid makeup valve trains (recirculator packages, chillers, & evaporators in excess of 20 tons [53 kW_t]) for moving piping as the solenoid cycles.

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