Engineering Practice

Waterhammer In Condensate Return Lines

Inserting high-pressure condensate into a low-pressure, pumped condensate-return line can cause waterhammer. Understand why and avoid it

FIGURE 1. The rupture of this check valve from a steam trap assembly allowed the condensate system to drain over 600 ft^3 of condensate over a long weekend into a steam vault, completely flooding it

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There is a temptation that steam design engineers find difficult to resist — to put condensate from high-pressure (HP) steam mains directly into the low-pressure (LP), pumped condensate-return (CR) mains. After all, the CR main is so convenient — it is generally laid right next to the outgoing steam main in the same tunnel, trench or racks as the CR main returning to the steam plant. And, the good practice alternatives to dumping the condensate directly into the pumped CR (such as running a dedicated separate HP condensate-return pipe back to the steam plant; or if a user's flash tank is not nearby, flashing the condensate in a small vented tank at each trap then pumping it back into the CR main), seem like swatting a fly with a sledge hammer. After all, we're only talking about flow from a few steam traps discharging maybe 50 lb/h, which is less than one cubic foot of water per hour for each one.

Admittedly, there are so-called work-arounds for this design problem that are less costly and complicated than the good practice alternatives, but I do not believe engineers have proof that they really work. The most popular of these alternatives, was the winner in a competition held years ago by a manufacturer's trap magazine to find the best work-around, but, I believe it failed to prevent the waterhammer that split the check valve pictured in Figure 1.

This article discusses what caused that failure, and gives engineers a criterion for determining if a pumped condensate-return line will hammer when high-pressure and high-temperature condensate is inserted into it. It only addresses what causes condensation-induced waterhammer, which occurs as a result of injecting HP condensate into a LP, pumped condensate return. It does not address column closure waterhammer, another common form of waterhammer in CR systems. Column closure waterhammer is addressed in Ref. 1.

Typical waterhammer scenario

Let us consider a typical scenario where HP condensate at the saturated steam temperature — say 338°F for 100 psi steam — exits the steam main through a steam trap whose pressurized discharge is piped directly into a CR main. The CR main is already flowing full of condensate that is being pumped from atmospheric condensate receivers in the basements of campus buildings or condensate collection points at steam consumers located upstream. The condensate pumps must provide enough pressure to hydraulically push and lift the condensate back to the steam plant — say 15 psig in this scenario. Because the condensate receivers are vented to the atmosphere, condensate received by them flashes to atmospheric pressure and 212°F (at sea level). After some tank and line losses, condensate temperature (in the pumped CR line heading back to the plant) is probably less than 200°F.

When the 338°F saturated condensate (from the 100-psi steam main) is discharged through the steam trap, it undergoes a pressure drop as it passes through the trap orifice to the pressure of the CR line — 15 psig in this scenario. At that pressure, 338°F water cannot exist. The hottest possible water temperature at 15 psig is the saturation temperature of water at that pressure (equivalent to 250°F). Therefore, 88 degrees (338 – 250°F) must be shed from the condensate. In the English system of units, one Btu corresponds to a 1.0°F change in temperature for 1 lb of water, so shedding 88°F pretty closely[1] corresponds to shedding 88 Btu/lb of condensate.

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[1] A video clip of watercannon can be viewed on the author's website at www.kirsner.org.

Now ask yourself, what happens to this energy?

The answer is that it goes into making steam. Consider that vaporizing an entire pound of 250°F condensate would require about 900 Btu (per the steam table). Since only 88 Btu of excess energy are available, about 10% of each pound of 338°F condensate leaving the 100-psi steam main for the 15-psi condensate system will vaporize to saturated steam, while the remaining 90% of condensate discharge remains in liquid form. So, by mass, there are nine parts water to one part steam entering the condensate return line.

But the masses of the two phases are not what we would notice if trap discharge were visible. We would notice the relative volume of the two phases. Volume wise, the specific volume of saturated steam at 15 psig is about 800 times that of an identical mass of liquid water. Thus, by volume, the ratio of steam to water looks like 800 parts steam to 9 parts water, or 89 to 1. Therefore, what you would see exiting the trap is predominantly steam with a fine water mist interspersed in the steam.

What we essentially have, then, when the HP condensate discharge enters the CR main is a large volumetric flow of saturated steam at 250°F entering a pumped CR line full of 200°F water at 15 psi. The water is subcooled roughly 50°F with respect to the entering steam. This is enough subcooling to support condensation-induced waterhammer. In other words, if the entering steam is able to blow a sizable bubble, which is subsequently surrounded by subcooled condensate, the bubble can abruptly collapse, thereby allowing the surrounding water to rush in to the void left behind by the disappearing steam and smack into itself. Depending on the size of the void, the overpressure from this waterhammer event can exceed 1,000 psi.

Is waterhammer guaranteed?

The answer, surprisingly, is no. And this explains why some steam systems are able to get away with injecting HP condensate into LP pumped condensate returns without severe waterhammer. What determines whether the two mixing flows will hammer as they mix is the ratio of the condensing capacity of the condensate flow to the heating capacity of the incoming steam flow. Researchers at Creare, Inc. first defined this ratio as $R_{c/s}$, although their notation and definition are modified slightly here for the scenario being discussed. $R_{c/s}$ is defined as follows:

If $R_{c/s}$ can continuously be kept >1.0 — plus a margin for imperfect mixing — waterhammer due to insertion of flash steam into subcooled condensate can be avoided

$$R_{c/s} = \frac{\text{Condensing capacity of the condensate flow}}{\text{Heating capacity of the steam flow}} = \frac{\dot{m}_c \Delta T_{\text{below saturation temp}}}{\dot{m}_s h_{fg}} \qquad \textbf{(1)}$$

Where:

m_s = the mass flow of flash steam, lb/h

m_c = the mass flow of subcooled condensate, lb/h

c_p = the heat capacity of water (1 Btu/lb-°F)

$\Delta T_{below\ saturation\ temperature}$ = the degrees of subcooling below the saturation temperature, °F

h_{fg} = heat of vaporization, Btu/lb

- ***If $R_{c/s}$ is < 1.0:*** there is not enough flowing condensate-heat capacity to condense all incoming steam flow, so steam bubbles will remain in the mix. The resulting two-phase mixture will not collapse in a waterhammer because there is not enough condensing capacity to allow it to do so. But, the flow is susceptible to hammering downstream if another subcooled-condensate flow merges with the bubbly mixture so that $R_{c/s}$ then goes over 1.0.
- ***If $R_{c/s}$ is initially > 1.0 and there is perfect mixing of the two streams:*** All steam will be condensed as it enters the flowing condensate return main and no steam bubbles will remain to collapse. Thus, if flows remain steady, the mix will not hammer. Call this the "stable" mixing region with respect to $R_{c/s}$. (Note, however, if $R_{c/s}$ is just slightly above 1.0 with imperfect mixing or stratification of the flows, some steam bubbles may persist temporarily and waterhammer would be possible. This is explained below).

The complicating factor in any normal steam system is this: Flows do not remain steady. Condensate pumps cycle on and off to maintain their receiver's tank level; blast discharge traps fire, then dwell, then fire again; and downstream in the CR main other condensate streams may tee-in heading back to the steam plant. All these events change the $R_{c/s}$ of the overall mixture stream. In what the author considers to be a landmark paper written in the mid 1980s for the nuclear power industry, each of these shifting conditions was tested as a function of $R_{c/s}$ with varying liquid-flow velocities to see when waterhammer occurred [2]. In these tests, steam was injected coaxially and cocurrently through a 2-in. injector pipe that was mounted to discharge axially down the middle of an 8-in. pumped condensate line as shown in Figure 2. One hundred and fifty tests for waterhammer were performed, of which about one-half exhibited waterhammer. The tests showed the following:

Case A: Sudden increase in condensate flow. If $R_{c/s}$ was initially < 1.0 in a mixture of constant steam and condensate flows (so that steam bubbles persisted in the mix) and condensate flow was suddenly increased (as if an additional condensate pump were started) so that $R_{c/s}$ exceeded 1.0, a waterhammer always occurred. The situation was similar if the condensate flow was ramped up from a lower flow to a higher flow, although water hammer did not occur in every instance. One waterhammer did occur with initial $R_{c/s}$ as high as 1.3 into the stable region — presumably the result of incomplete initial mixing, which allowed some bubbles to persist.

Case B: Abrupt shutoff of steam flow. Likewise, if $R_{c/s}$ was initially still < 1.0 in the mixture but instead of condensate flow increasing, steam flow

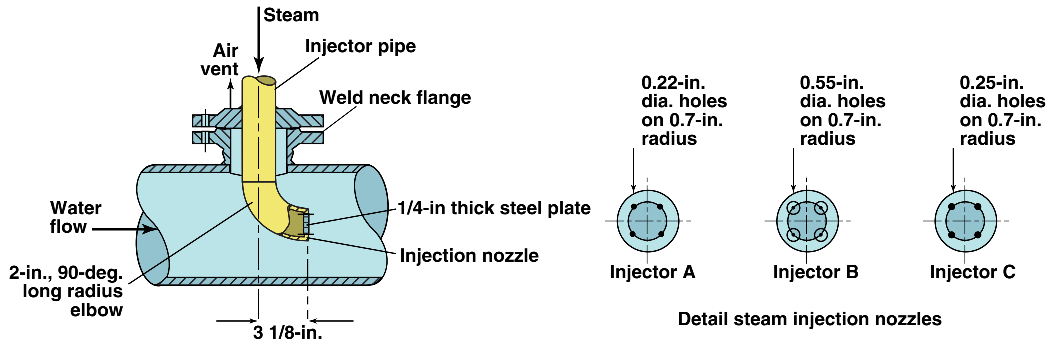

FIGURE 2. **In tests, steam was injected coaxially and cocurrently through a 2-in. injector pipe that was mounted to discharge axially down the middle of an 8-in. pumped condensate line as shown here [2]**

were abruptly shut off, then again waterhammer generally occurred, as in Case A above as the $R_{c/s}$ abruptly increased above 1.0. An everyday example of this circumstance occurring might be the cycling off of a large blast-discharge trap where its discharge had been sufficient to cause $R_{c/s}$ to locally be < 1.0 in the condensate return line. In some experimental runs — presumably due to incomplete initial mixing — waterhammer was recorded in these circumstances with initial $R_{c/s}$ as high as 1.1.

Case C: High point in pipe coupled with steam shutoff. When a high point was constructed in the condensate pipe during the experiments — specifically a 5% up-sloping pipe joined a 5% down-sloping pipe just downstream of the trap discharge — waterhammer occurred when steam was shut off, even if initial $R_{c/s}$ was as high as 1.4 in one instance and 1.2 in two other instances. This indicated that even though the initial $R_{c/s}$ exceeded 1.0, steam could collect at the high point in the line and persist there long enough to hammer when $R_{c/s}$ was suddenly increased by shutting off steam inflow.

Calculation of $R_{c/s}$ along with these tests provide a roadmap for the troubleshooter to determine what is causing waterhammer when high-pressure and high-temperature condensate is inserted into relatively low-pressure, subcooled pumped CR lines. I stipulate "pumped" because I'm speaking of lines that are completely full of water that are pressurized (or else they would be little motive force to accelerate the water into the void left by collapsing steam) and "subcooled" with respect to the pressure in the line (or else the flashed steam would not rapidly condense to form a void). Of course, the subcooled water need not be pumped but could be flowing under pressure for any other reason. An example would be a high-pressure, high-temperature bypass blowdown from a once-through steam generator (OTSG) coming off line and then mixing in a common line with the cooler bypass blowdown that is discharging from another OTSG being brought on line.

For the designer who wants to "get away with" injecting high-pressure and high-temperature condensate into a pumped condensate return main without waterhammer, the utility of the $R_{c/s}$ is straightforward: keep $R_{c/s}$ >1.4 (1.0 plus a margin for imperfect mixing of 0.4) so that all steam is being condensed by subcooled flow as it enters the condensate return line and, thus, never has a chance to create a steam bubble of any size that can collapse in a condensation-induced waterhammer. Keep in mind that even if $R_{c/s}$ goes below 1.0 at any point in the condensate return system, water hammer is not guaranteed. But, the system is susceptible to hammering if either of the following circumstances changes in the mix:

1. A large blast-discharge trap cycles off
2. Another subcooled condensate flow merges with the CR line downstream

Watercannon

The foregoing discussion has been about waterhammer occurring in the CR main. Watercannon, in contrast, occurs within the discharge piping from the steam trap, which is discharging flash steam and condensate into a pumped CR main. The term, watercannon, refers to water hammer in a vertical tube that is injecting steam vertically downward into a cold pool. [2]

When the flow of high-pressure and high-temperature condensate from the trap shuts off, flash steam is left in the discharge pipe and is entrapped between the closed steam trap and the subcooled water in the condensate return line. If the water is subcooled more than 40°F, the flash steam can rapidly condense, leaving a relative vacuum in the discharge line. The pressure in the condensate return line will then accelerate condensate back up the trap discharge line, causing it to slap into the steam trap or check valve if there is one protecting the trap. Watercannon experiments in the laboratory with water pushed by just atmospheric pressure have recorded more than 1,000 psi overpressure on the valve being struck, when the water is halted.

This is what I believe happened to the check valve pictured at the beginning of this article. It was installed as shown schematically in Figure 3. Listed below is the perfect storm of conditions that I believe enabled the waterhammer that split the check valve body and then a description of what I believe happened.

1. The trap assembly discharged condensate from a 60-psi steam main (saturation temperature = 308°F) to an adjacent, pumped condensate-return line returning sub-200°F condensate back to the steam plant from a single condensate receiver and set of duplex pumps in an upstream building.
2. The duplex pumps in the building cycled on and off to maintain the level in the condensate receiver.
3. The steam trap discharging 60-psi saturated condensate into the pumped condensate return line was a thermodynamic trap (equivalent to a blast-discharge type trap).
4. The engineer used the scheme depicted in Figure 3 to inject the HP condensate into the pumped CR

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[2] The exiting steam will blow steam bubbles in the pool, and the bubbles will rapidly condense and collapse. If the steam entry point at the top of the tube is choked or has been valved off completely (so that source steam cannot supply makeup steam to the tube as fast as the steam condenses), pool water can be accelerated up the tube into the collapsing steam void in the tube, slamming into the valve that is restricting steam flow at the top of the tube.

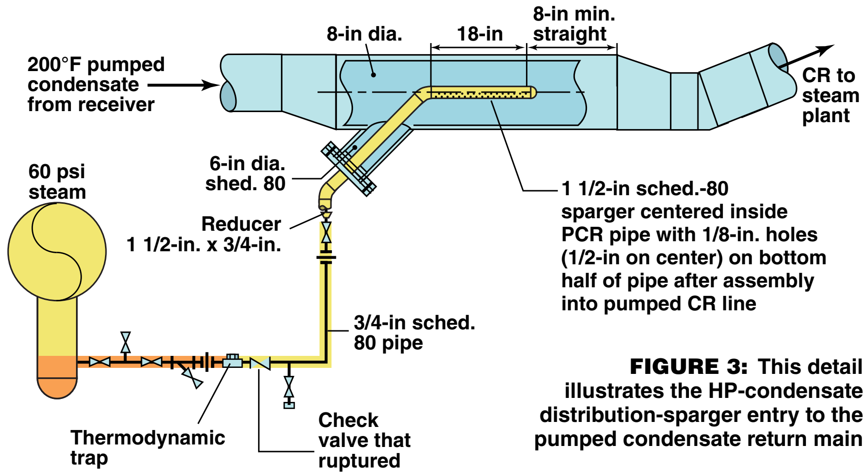

FIGURE 3: This detail illustrates the HP-condensate distribution-sparger entry to the pumped condensate return main

main. The idea of the sparger was to break up the flash steam into small bubbles as it enters the condensate return so that any bubble collapse would not involve a large movement of water.[3] This probably works to aid mixing if $R_{c/s} > 0$. I presume it does not help if $R_{c/s} < 1.0$. As far as I know, this idea first appeared in a steam-trap manufacturer's magazine as the winner of a competition to identify the best way to avoid waterhammer while injecting high pressure condensate into a low-pressure, pumped condensate return. The scheme has been repeated in other publications from other sources since then but I am not aware of it ever being rigorously tested.

5. The free area of the sparger holes exceeded the free area of the inside of the distributor pipe, so there was not much restriction to the backflow of condensate from the CR Main.

Under these conditions, the thermodynamic trap would have discharged flash steam into the CR main periodically when the condensate return pumps were off, so there was no condensate flow from upstream. Essentially, the $R_{c/s}$ would have been 0, allowing flash steam bubbles to persist in the CR Main. The 8-in. expanded pipe sleeve, shown in Figure 3, gave a convenient site for flash steam that did not move downstream to collect because of the high point created by the leaving eccentric reducer. The steam bubbles, which did not buoyantly move uphill in the CR system, would have coalesced into a large bubble in the 8-in. sleeve of the distribution sparger.

The calculation in the box (p. 37) shows that when the condensate return pumps in the upstream building cycled on, the Rc/s of the mix of flowing condensate and trap discharge would have gone to well above 1.0, even if the steam trap was still firing. Thus, the steam bubbles in the CR main that were exposed to the onslaught of subcooled condensate would have collapsed. Collapse of the large steam bubble lodged in the 8-in. sleeve would have been particularly violent. The inrushing water from the pumped condensate and the back flow of condensate in the CR line would have collided in the collapsing steam void. In addition, if we imagine that the trap had just cycled off so that the trap discharge pipe was still full of flash steam, the pressure of the incoming water columns would have forced water back through the holes of the 1 ½–in. sparger and accelerated it down the ¾-in. trap discharge piping toward the thermodynamic trap.[4] The water column would have been halted, however, by the check valve, which absorbed the impact of the waterhammer collision. Besides jerking the condensation return piping, the resulting waterhammer overpressure would have exerted a hoop stress in the check valve and the ¾-in. piping leaving the check valve. Examination of the check valve showed that the rupture occurred on the downstream side of the flapper where the water column would have struck. The sparger assembly was not available for inspection as it had been disposed of by the time of my investigation.

Could the watercannon have been prevented by a different nozzle design? The tests cited in Ref. 2, examined the effects of three different outlet-nozzle designs on the waterhammer in the condensate return main and steam discharge piping. The nozzles were flat, round plates affixed to the end of a 2-in.-long radius elbow, which entered the 8-in. pipe, turned 90 deg., and discharged steam along the axis of the pipe as shown in Figure 2. The injector plates had four holes drilled concentrically on a 0.7–in. radius from the center of the plate, with the only difference being the hole size as described below.

a. Nozzle A: Four 0.22-in. dia. holes; 4.5% net free area
b. Nozzle B: Four 0.55-in. dia. holes; 28% net free area
c. Nozzle C: Four 0.25-in. dia. holes; 5.8% net free area

In the experiments, watercannon was suppressed with Nozzles A and C. It only occurred within the discharge pipe terminated with Nozzle B — the injector with the greatest free-opening area. Apparently, the openings in Injectors A and C restricted the inflow of water so that a substantial velocity could not develop in the discharge pipe heading back toward the check valve and trap. Otherwise, the performance difference in the different injectors was not remarkable. All three vibrated and shook as steam ejected from them and collapsed when $R_{c/s} > 1.0$. The suppression of waterhammer by the restricted nozzles suggests a possible deterrent to watercannon in HP, high temperature trap-discharge lines into LP condensate-return lines.

Outcome of another popular workaround scheme. It is worth noting that there were three other vaults on the pipe run back to the steam plant in which HP traps discharged condensate from the 60-psi steam main into the CR main. There was no waterhammer damage at these vaults nor reports of waterhammer noises as far as I know, even though the $R_{c/s}$ would have greatly exceeded 1.0 in the CR main at these sites, too, when the upstream condensate return pump energized. These three vaults did not

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[3] Water moving into a void needs non-negligible void volume in order to accelerate to an appreciable velocity to cause water-hammer.

[4] The dropping pressure could have, at most, fallen to as low as the vapor pressure of the onrushing condensate. At a temperature of about 200°F, the vapor pressure is about 12 psia.

CALCULATION OF $R_{C/S}$ ONCE THE CONDENSATE PUMP CYCLED ON

1. The trap capacity was about 500 lb/h. The saturation temperature of 60-psig condensate temperature is 308°F. The lift to the steam plant from the location of the vault was 40 ft, requiring 17 psi of pressure in the CR line. The saturation temperature of 17 psig is 254°F. That means that the 308°F condensate had to shed 54°F ($\Delta T_{above\ saturation\ temperature}$) to exist at 17 psig. Assuming a specific heat, c_p, of 1.0 Btu/lb °F, that is equivalent to 54 Btu/lb. So the amount of flash-steam heat that would have to be absorbed to condense all potential flash steam ($m_s h_{fg}$) was at most 500 lb/h × 54 Btu/lb = 27,000 Btu/h, or 450 Btu/min.
2. If condensate cooled to 200°F, while sitting in the condensate receiver tank waiting to be discharged, then relative to 17 psig, it has 254–200 = 54°F of subcooling ($\Delta T_{below\ saturation\ temperature}$). Again, assuming a c_p, of 1.0 Btu/lb °F, that is equivalent to 54 Btu of cooling capacity per pound of condensate. Thus, if each pound of condensate can neutralize 54 Btu of steam, the required condensate flow to neutralize 450 Btu/min of flash steam energy is: 450 Btu/min / 54 Btu = 8.33 lb/min. This rate of 8.33 lb/min is equivalent to a little more than 1 gpm of condensate flow (m_c).
3. So 1 gpm is the condensate flow needed to merely absorb all flash steam energy from the trap discharge while it is discharging. If condensate flow exceeds this amount, all flash steam will be condensed.
4. Each 5-hp duplex condensate pump that was part of the upstream condensate receiver assembly was selected to move 60 gpm at 60 psi pressure differential. Assuming the pump operated at this point on its pump curve, and the trap was firing, $R_{c/s}$ with the pump and trap on would have been 60 gpm / 1gpm = 60. ❑

utilize a distribution sparger to break up flash steam entering the CR main. Instead they contained finned heat-exchange tubing downstream of the traps through which the condensate flowed to reject heat into the vault before it was injected into the CR main. This arrangement would have at least limited the amount of flash steam injected into the condensate return. An advantage these vaults had is that they were downstream (in terms of the condensate return's flow direction) of Vault 4. Therefore, the condensate reaching these downstream vaults was somewhat prewarmed by steam injection upstream at Vault 4 before it reached them and thereby had less subcooling available to collapse flash steam.

Did the degree of subcooling of the pumped condensate matter? The $R_{c/s}$ factor incorporates both the flowrate and subcooling of the condensate flow, so it is not clear from Ref. 2 tests whether or not there was a minimum subcooling below which no waterhammer, including watercannon, could take place. The experiments were run with subcooling, which was purposely varied between 50 and 175°F to see if subcooling was an important parameter. With regard to the severity of the waterhammer collapses, the degree of subcooling did not seem to be, by itself, significant. The researchers did not, however, check to see if there was a minimum subcooling necessary to support waterhammer in the CR main.[5]

Summarizing advice

If high-pressure and high-temperature condensate is to be injected into a pumped condensate return line:

1. Maintain an $R_{c/s} > 1.0$ continuously, for the mix of the trap discharge with the pumped CR (plus a margin for poor mixing of about 25%; or, if you've got high points in the CR main where steam can collect, a margin of about 50%). To aid in maintaining this condition:
   - Provide variable flow CR pumping (as opposed to on/off control) in an effort to maintain flow as steady as possible
   - Avoid blast discharge traps like inverted bucket traps in favor of modulating discharge traps. Thermostatic traps with high subcooling settings seem like a good idea to me as long as drip legs are sized to handle the condensate backup
   - Avoid piping designs with local high points where flash steam may temporarily collect
2. Do not try to inject the discharge from HP traps directly into a pumped CR Main if there is only one set of CR pumps upstream and operating in an on/off mode

Keep in mind, the higher the pressure is in the CR main, the more forceful the condensation-induced waterhammer will be in the condensate return system. Pressure gauges, or at least ports for them, should be provided in the CR main to calculate the $R_{c/s}$ in order to troubleshoot problems.

Even with $R_{c/s}$ >>1.0, watercannon within trap discharge lines can still be a problem. In fact, I do not understand why it is not more of a problem when high-pressure cycling traps discharge into low-pressure, pumped condensate-return lines. Most steam-main trap assemblies, after drawing condensate off drip legs near ground level, lift the condensate in a ¾-in. pipe run to above the CR main, then turn down to drop the trap discharge into the top of the pipe. This configuration seems perfect to me for watercannon when the traps cycle off. Most trap assemblies, as far as I have noticed, do not seem to suffer from watercannon when the traps cycle closed. Thus, I hesitate to recommend that restrictive nozzles like Nozzle A and C (shown to suppress waterhammer in Ref. 2 tests) be provided at all high-pressure and high-temperature trap-discharge outlets into low pressure CR lines.

Where there is a problem, however, another simple solution appeared to work in one case on which I consulted. Waterhammer was occurring in the discharge piping from HP inverted bucket traps into a pumped CR main running in a pipe rack about 9 ft above the traps. The owner, upon my suggestion, placed an additional check valve just upstream of the discharge into the CR line at the top of a piping rack. That stopped the hammering by preventing the condensate in the CR main from accelerating all the way down the vertical rise to slam the trap assembly 9 ft below when the trap cycled off. ■

Edited by Rebekkah Marshall

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[5] 20°C is generally considered to be the minimum subcooling to enable condensation induced waterhammer, but there is no minimum subcooling required where flow is motivated to move into a steam bubble by, say, a pump starting.