Government of Western Australia
Department of Mines and Petroleum
Resources Safety

# Mines Safety Bulletin No. 92

**Date:** 29 July 2010

**Subject:** Condensation-induced water hammer events — potential consequences of allowing steam and sub-cooled water or slurry to mix

## Summary of hazard

This safety bulletin is prompted by concern relating to a recent incident involving condensation-induced water hammer. Although the particular incident did not result in a fatality or serious injury, there was loss of containment and a significant release of energy. The resulting pipe-whip caused severe damage to the surrounding plant, had a high potential for serious injury or fatality, and resulted in considerable production downtime.

Reports received by Resources Safety suggest that this is not an isolated industrial occurrence. This bulletin serves as a reminder to responsible persons at mineral refineries to review current standard operating procedures for steam-slurry systems. Operators are urged to review systems where steam is in contact with sub-cooled liquids or slurries, especially during non-routine events, such as unplanned power outages, plant start-ups or shutdowns, and process equipment on standby.

Condensation-induced water hammer results from the rapid condensation of steam when sealed off by sub-cooled condensate in an enclosed system, such as a pipeline. "Sub-cooled" means that the liquid or slurry has cooled 30°C or more below the saturation temperature of the steam with which it is in contact.

Condensation-induced water hammer may also be referred to as "rapid steam bubble collapse". The phenomenon is not limited to water and steam systems. Process equipment is also at risk, particularly pipelines where sub-cooled slurries and steam are in direct contact.

Figure 1 shows a pipeline where steam and sub-cooled liquid condensate or slurry are in direct contact. Prior to the fluid draining through the valve, the horizontal pipe is full, so steam is not in contact with condensate or slurry along the length of the pipe. The condensate in the line cools due to heat loss through the pipe walls.

When liquid condensate or slurry is drained from the formerly full line by opening a valve, steam can enter the horizontal line. The steam in the line condenses due to contact with the pipe walls as well as the sub-cooled liquid or slurry. As the steam condenses, it induces more steam to flow into the low-pressure void. This flow of steam over the condensate draws up waves, via the Bernoulli effect.

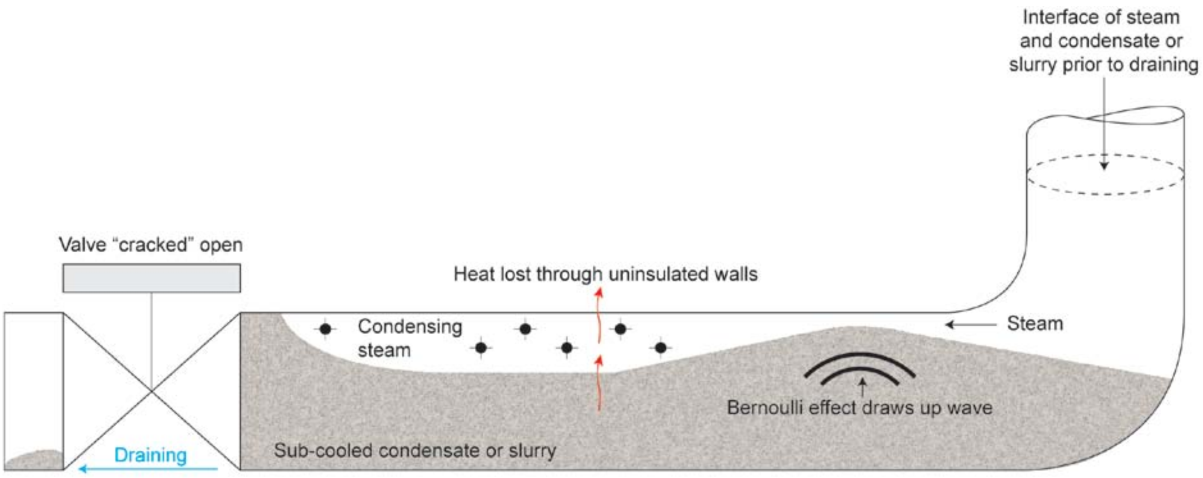


*Figure 1 Steam influx, via the Bernoulli effect, draws up a wave of condensate or slurry*


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*Note: For horizontal fluid flow, an increase in the flow velocity to get by a restriction results in a decrease in the static pressure. The equation describing this effect is known as Bernoulli's law.*

If the rate of steam inflow is rapid enough, the inrush of fresh steam can draw up a wave of liquid or slurry that plugs the pipeline. This isolates a steam pocket within the sub-cooled liquid condensate or slurry, as shown in Figure 2.

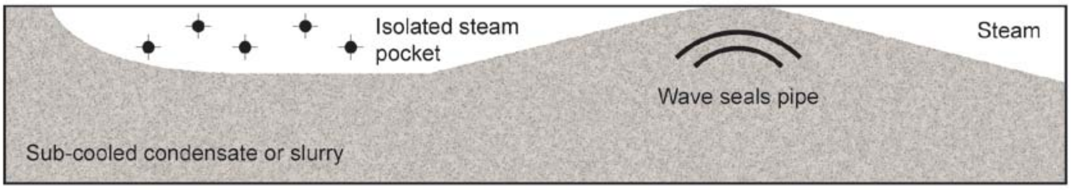


*Figure 2 Rapid heat transfer creates a significant Bernoulli effect and seals steam in isolated pocket*

The continued rapid condensation of steam inside the isolated pocket (which is cut off from steam replenishment) decreases the pressure in the void. The difference in pressure between the high pressure steam and the collapsing steam void causes the water (or slurry) plug and surrounding fluid to rush in to fill the low pressure void, as shown in Figure 3.

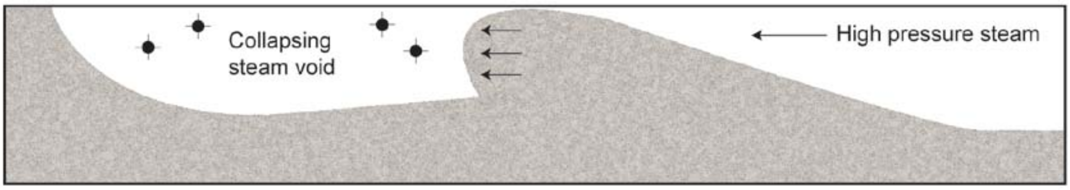


*Figure 3 A pressure front is created by the collapsing steam void inside the pipeline*

The water or slurry "slaps" into itself. The change in momentum of the inrushing incompressible fluid is converted to overpressure (Figure 4). This overpressure wave travels in both directions from the site of the collapse, and may be sufficient to Blow out gaskets or rupture pipe elements.

If there is a rupture, the thrust from the liquid and slurry escaping from the pipe can be calculated as follows (in SI units).

T = 2,000 x p x A x sin (θ/2), where T is the thrust in newtons (N), p is the internal pressure in kilopascal (kPa), A is the area of the opening in $m^2$, and θ is the bend angle in degrees. The factor of 2,000 assumes frictionless flow (or a short pipe) and an orifice coefficient of 1.0 (i.e. discharge not affected by downstream pressure).

For a straight pipe (i.e. θ = 180°), the sin (θ/2) term reduces to 1 and the thrust calculation simplifies to 2,000 x p x A.

For example, a 10" schedule 80 pipe (area of 0.046 $m^2$) discharging liquid at 3,250 kPa (465 psi) through its entire area will do so with a thrust of up to 301,140 N (67,000 pounds force). The potential consequences of this discharge include significant plant damage and serious or fatal injuries.

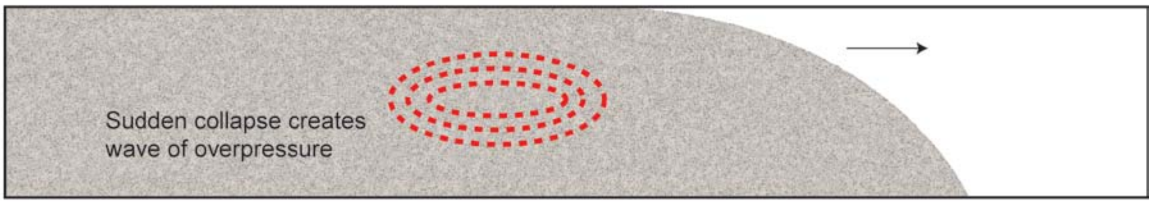


*Figure 4 An overpressure wave is generated that travels the length of the water- or slurry-filled portion of the pipe*

## Contributory factors

Factors determining the occurrence and severity of condensation-induced hammer include:

- *Steam pressure*: The motive power for accelerating the liquid condensate or slurry is supplied by the differential between the surrounding steam pressure and the collapsing pressure within the void. Higher steam pressure will result in higher fluid velocities and more powerful hammer events.
- *Degree of condensate sub-cooling*: A more sub-cooled condensate implies a larger thermal energy differential (or driving force) for condensation between the steam and condensate.
- *Presence of non-condensable components left in the void*: The presence of non-condensable species serve as a cushion to the impact of condensation-induced water hammer. It is common for process steam to be produced from de-aerated feed water, which means that dissolved air (and other non-condensable species) has been removed from the feed water.
- *Size of the low-pressure void left by rapidly condensing steam*: A larger void will allow the inrush of liquid condensate or slurry to reach a higher velocity before crashing to a halt.
- *Pipeline slope*: The steam bubble must first become entrapped by condensate before it can create condensation-induced hammer. This cannot happen during draining in a vertical line where steam is atop condensate (unless draining is extremely rapid). The greatest risk is associated with draining where steam enters horizontal lines. In addition, the slope of the line will determine where liquid or slurry accumulates.
- *Pipeline geometry*: Once the pressure wave is generated, the weakest fitting filled with water or slurry will be the one most susceptible to rupture.

## Action required

High-pressure steam in contact with sub-cooled condensate or slurry is an unstable mixture, which may be subject to condensation-induced water hammer at any time.

Operators should refrain from:

- draining a liquid line under steam pressure that allows steam to enter the formerly liquid-filled line, especially if the liquid is sub-cooled with respect to the steam; and
- allowing sub-cooled liquid to be pushed or drawn into a steam-filled line.

If sub-cooled condensate is in contact with steam (e.g. a vertical section of line above a horizontal section), do not drain the condensate or slurry from the line. Instead, isolate the steam and let the pressure subside. The condensate may then be bled off.

Engineers, operators and maintenance personnel must be trained to ensure awareness of this phenomenon and its potential consequences.

## Further information

Kirsner, W., 1999. *Condensation induced water hammer*. Published in Heating/Piping/Air Conditioning Magazine. Available from www.kirsner.org/kce/media/pdfs/KirsnerHammer.pdf [as viewed 13 June 2010]

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Mr Wayne Kirsner, Professional Engineer, assisted in the writing of this safety bulletin.