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How Steam-conditioning Valves Improve Your Process

WHITE PAPER



SMART IN FLOW CONTROL.

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Introduction

Superheated steam can be found in various different applications and industries, ranging from refineries, power, chemical, and petrochemical plants to pulp and paper, food and beverage as well as pharmaceuticals. Superheated steam is desirable for many processes; however, downstream of these processes, it may be advantageous to reduce the steam pressure and temperatures to improve process efficiency, protect equipment, or perform other processes. In industrial settings, this is most commonly done by using a control valve to reduce the steam pressure and a desuperheating nozzle to reduce the steam temperature. While this typical setup will often perform the task to an acceptable standard, it may also require longer-than-necessary straight pipe lengths, lead to less accurate temperature control, limit the total steam temperature reduction, and limit the range of process conditions in which the system can acceptably perform the desired task. Alternatively, a steam-conditioning valve (also referred to as a steam-converting valve or steam-desuperheating valve) can be used, which combines the steam pressure control valve with the desuperheater in one unit. Some of the clear advantages of using a steam-conditioning valve as a combined system are superior temperature control, maximum turndown as well as reduced space and construction cost thanks to the compact design.

This article will detail the physics involved in steam desuperheating, the most common desuperheating nozzle types available on the market including their advantages and disadvantages, the functionality of steam-conditioning valves, the increased performance compared to different desuperheating nozzle systems, and practical examples of steam-conditioning valves used in several different industrial processes.

The physics of desuperheating

There are two basic methods of reducing steam temperature: surface cooling and direct injection cooling. Surface cooling is performed by means of a heat exchanger: a coolant flows through a series of tubes and superheated steam flows past these tubes, reducing its temperature. This method is very rarely used, mainly for applications where the coolant must not come into contact with the steam. Coolers of this type are typically bulky, expensive, and difficult to control.

Desuperheating by direct water injection is considerably simpler in terms of hardware required and safer in its control characteristics. Here, water is injected directly into the steam flow and as it evaporates, the latent heat of the superheated steam is reduced. The heat transfer from the steam to the water droplet can be calculated as:

$$Q = A \cdot \alpha (T_S - T_W) \cdot \Delta t \quad (1)$$

- Q: amount of heat
- A: surface area of the water droplet
- α : heat transfer coefficient
- T_S : steam temperature
- T_W : water temperature
- Δt : time interval

The smaller the water droplets are, the larger the contact area (A) between the steam and the water droplets. Therefore, it is very important that the water is atomized in very fine droplets when it is injected into the steam flow. Atomization takes place in two steps: primary and secondary atomization. Primary atomization refers to the atomization by the desuperheater. The breakup of the water droplets by the dynamic forces of the steam flow is called secondary atomization. Secondary atomization occurs when the dynamic forces trying to deform a water droplet are greater than the surface tension forces that hold the water droplet together. This ratio is known as the Weber number (We):

$$We = \frac{\text{Dynamic force}}{\text{Surface tension force}} = \frac{\rho v^2 D}{\sigma} \quad (2)$$

- ρ : steam density
- v : relative velocity between the steam and the water droplet
- D: diameter of the water droplet
- σ : surface tension of the water droplet

Secondary atomization begins to take place at a Weber number above 12; it occurs faster as the Weber number increases.

The most influential factor on the Weber number is the steam velocity: a higher velocity leads to a higher Weber number. The following images show the breakup of a water droplet for Weber numbers of 14.5 and 51.

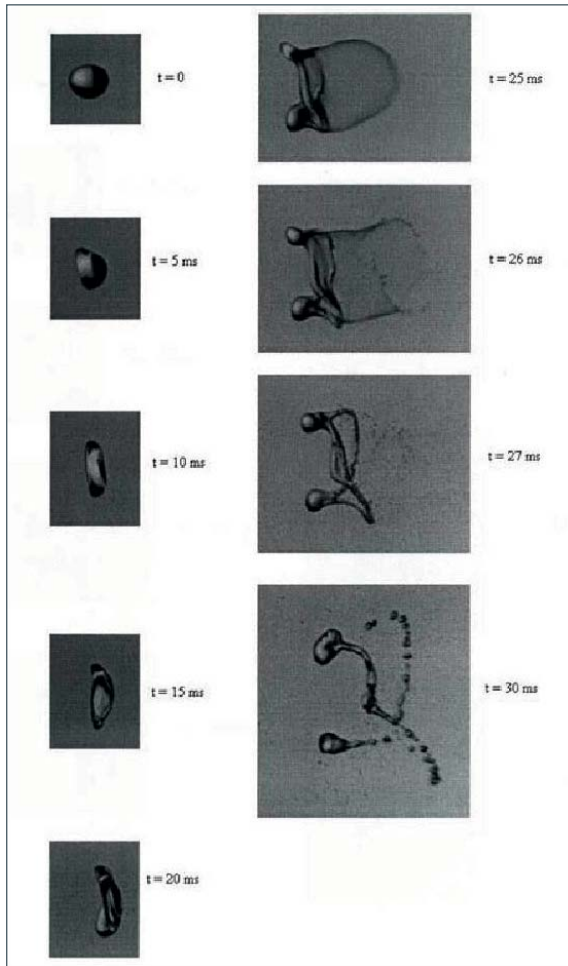


Fig. 1: Breakup of a 3.7 mm water droplet, $We = 14.5$
(source: Majithia et al. (2008))

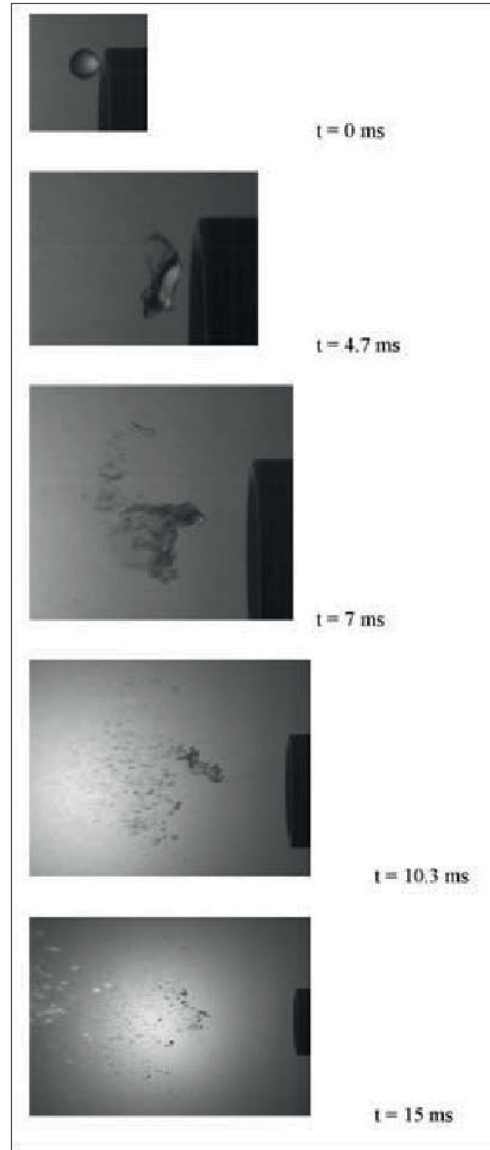


Fig. 2: Breakup of a 3.0 mm water droplet, $We = 51$
(source: Majithia et al. (2008))

The heat transfer coefficient (α) also depends on the steam velocity. When water droplets first come into contact with superheated steam, a steam envelope with an insulating effect forms around the water droplet. The larger the relative velocity is between the water droplet and the steam, the faster the steam envelope around the water droplet is blown away, which has a positive effect on the heat transfer coefficient.

Equation 1 mentioned above dictates that colder injection water means a larger temperature difference between steam and water and therefore a higher overall heat transfer rate. However, colder water droplets need more time to evaporate and when they collide with the piping system, they cause thermal stress.

Additionally, hot water has a lower surface tension than cold water, which increases the Weber number and thus supports the secondary atomization effect. As a general rule, the injection water for steam desuperheating should have a temperature of at least 80 °C.

Besides the steam velocity at the point of water injection and the water temperature, there are other important parameters when sizing and selecting a desuperheating system for a specific process. The most important parameters are:

Downstream steam temperature: All water injection steam desuperheating systems require a residual amount of superheat in the downstream steam flow to fully evaporate the injected water. The amount of residual superheat required for the system to function is dictated by the design of the desuperheater unit. Very often, the closer the steam temperature is to saturation, the more efficient your process will be because saturated steam has a better heat transfer coefficient and is easier to control than superheated steam.

Water-to-steam ratio: The ratio of the mass flow rate of water required to cool the steam to the desired temperature to the mass flow rate of steam. The required amount of water to cool the steam is calculated based on two fundamental principles of physics: the law of conservation of mass and the first law of thermodynamics (conservation of energy). Assuming the desuperheater system functions as a closed-loop adiabatic process, these two laws can be used to derive the following equation to determine the amount of injection water required to cool the superheated steam to a specific temperature:

$$\dot{m}_W = \dot{m}_{OS} * \frac{h_{OS} - h_{IS}}{h_W - h_{IS}} \quad (3)$$

- \dot{m}_W = mass flow rate of water
- \dot{m}_{OS} = mass flow rate of the outlet steam
- h_{IS} = enthalpy of the inlet steam
- h_{OS} = enthalpy of the outlet steam
- h_W = enthalpy of water

As the desired steam temperature reduction increases, so does the required amount of injection water. However, if too much water is injected, the water may not

mix properly with the steam depending on the method of desuperheating. As a result, the excess water may become dislodged from the steam flow and not evaporate. This leads to poor temperature control and potential problems for downstream equipment.

Steam velocity in the pipeline: A minimum steam velocity of approximately 5 to 10 m/s in the pipe must be maintained to ensure that the water droplets remain suspended in the steam flow until they are completely evaporated. The higher the steam velocity, the greater the turbulence in the pipe, which enhances mixing. If the steam velocity is too high, however, the water droplets still present in the steam flow may damage the pipeline. Furthermore, high steam velocities can generate system vibration, which leads to fatigue and potentially catastrophic failure of the desuperheating system or other equipment. Therefore, most guidelines suggest a maximum steam velocity between 50 and 80 m/s.

Steam turndown: Steam turndown describes the ratio of maximum steam flow to minimum steam flow that a device can effectively achieve. In practice, this value is often limited by the permissible velocities in the steam pipeline.

Water turndown: Water turndown is the ratio of maximum water flow to minimum water flow that can be used with a particular type of desuperheater to effectively reduce the steam temperature. It has a direct effect on steam turndown.

Distance to temperature sensor: Positioning the temperature sensor closer to the desuperheater unit reduces the control loop's dead time. However, it is important that the water droplets are completely evaporated before they reach the temperature sensor. Otherwise, the remaining water continues to evaporate downstream, lowering the final steam temperature. Additionally, the droplets may cling to the temperature sensor and provide an incorrect temperature reading.

Straight pipe run: The straight pipe distance required downstream depends on the process parameters and the mixing efficiency of the steam desuperheating device used. This distance should not contain elbows, valves, or other obstructions. If the straight pipe run downstream of the desuperheater is too short, unevaporated water droplets hit the pipe wall at the elbow and

become dislodged from the steam flow, which reduces steam cooling and therefore increases the amount of water required to reach the desired temperature set point. If the water-to-steam ratio exceeds the defined limit, there is the danger of the temperature set point never being reached. Also, the water dislodged from the steam may moisten the temperature sensor, which worsens the controllability of the process. The dislodged water also causes erosion at the pipe elbow.

Traditional nozzle desuperheaters

Fixed nozzle desuperheaters

A fixed nozzle desuperheater is the most basic type of water injection steam desuperheater; it consists of a stationary nozzle positioned directly in the main steam pipeline. The desuperheater sprays cooling water directly into the steam line to reduce the steam temperature. The nozzle acts as a fixed-area throttle. Therefore, the droplet size of the cooling water is a direct result of the water pressure drop at the nozzle orifice. The water flow rate is controlled by a separate control valve, which receives its signal from the temperature control loop.



Fig. 3: Fixed nozzle desuperheater

This type of desuperheating system is a cost-effective solution when there are small variations in steam flow. At partial steam loads (e.g. during start-up or shutdown operation), however, less cooling water is required to reach the same downstream temperature. With a fixed area to throttle the cooling water, a smaller pressure

drop is implemented across the nozzle and thus, the atomizing energy is considerably reduced. The droplet diameters considerably increase and evaporation becomes sluggish. The result is excess cold water in the hot steam line, which leads to high thermal stress gradients in the pipe wall as the bottom is colder than the top. This can cause cracking of weld seams or deform the pipe. Because of that, the turndown of fixed nozzles is typically limited between 3:1 and 5:1 (see Bartscher (1987) and Harris (1998)).

Variable-area multi-nozzle desuperheaters

A variable-area multi-nozzle (VAMN) desuperheater, similar to a fixed nozzle desuperheater, is installed inside a steam pipeline to inject cooling water directly into the steam flow. However, VAMN desuperheaters are superior to fixed-area nozzle desuperheaters in an important way: VAMN desuperheaters have a cluster of nozzles located in the steam flow and inside the desuperheater, there is a plug that moves up and down to control the water flow and the number of active nozzles in the steam flow.



Fig. 4: Variable-area multi-nozzle desuperheater

This eliminates the need for a separate control valve to regulate the water flow and allows the system to maintain a higher pressure drop across the nozzles over a much wider range of flow rates, which leads to small water droplets and better water atomization across this range. On the one hand, this gives the VAMN desuperheater a much better turndown ratio, typically between 10:1 and 12:1.

On the other hand, VAMN desuperheaters require a higher overall cooling water supply pressure. Also, high temperature differences or temperature swings between the cooling water and the hot steam can result in thermal stress, which is especially problematic as the control element is located in the steam flow. This can lead to the plug getting jammed or thermal cracks forming in critical components, e.g. nozzles, the lower body, and piston rings (see Sherikar/Borzsony (2006)).

Venturi desuperheaters

A Venturi desuperheater works by reducing the cross-sectional area of a steam pipeline at a certain pipe section and therefore, increasing the steam velocity and turbulence to better mix the water with the steam. Also, the nozzle head is often designed so that a portion of the steam flows in the spray nozzle head to assist in atomizing the water. The great water atomization achieved by the Venturi desuperheater allows for downstream steam temperatures closer to saturation and higher water-to-steam ratios than fixed nozzle and VAMN desuperheaters. However, the Venturi desuperheater requires relatively high steam velocities to achieve good water atomization, which means the steam turndown ratio is typically limited to about 5:1.

Steam-conditioning valves

Steam-conditioning valves combine a steam pressure reducing control valve with a desuperheating system in one unit. The steam pressure or flow rate is controlled by the position of the plug in the steam-conditioning valve while a water control valve regulates the flow of the injected cooling water and thus the temperature.

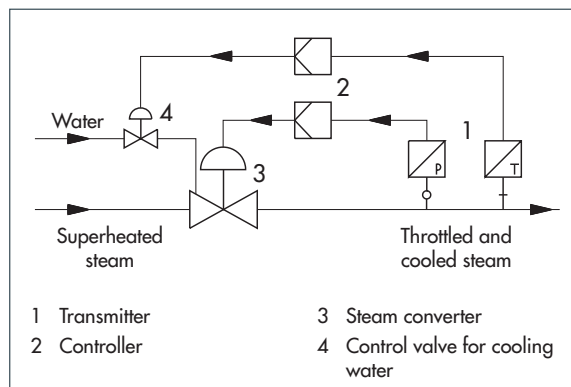


Fig. 5: Steam-conditioning control loop

Principle of operation

During the throttling process in a control valve, pressure energy is converted into kinetic energy, which reduces the pressure of the medium (in this case steam) and increases its velocity. The point of highest steam velocity occurs directly between the seat and plug, usually referred to as the “vena contracta”. Steam-conditioning valves use the high steam velocity near the vena contracta to create the smallest water droplets.

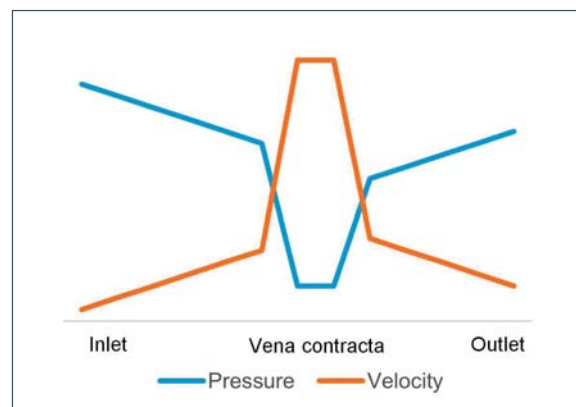


Fig. 6: Pressure and velocity profile across a control valve

The most typical steam-conditioning valve constructions will either attach a traditional nozzle injection system to the outlet of the steam pressure control valve, inject the water through the plug stem of the steam pressure reducing valve to try and inject the water as close to the vena contracta as possible, or divert a small stream of the high-pressure “atomizing” steam through a separate channel to the outlet of the steam pressure control valve, where the difference in steam pressure will atomize the water being injected into the steam.

The SAMSON steam-conditioning valve

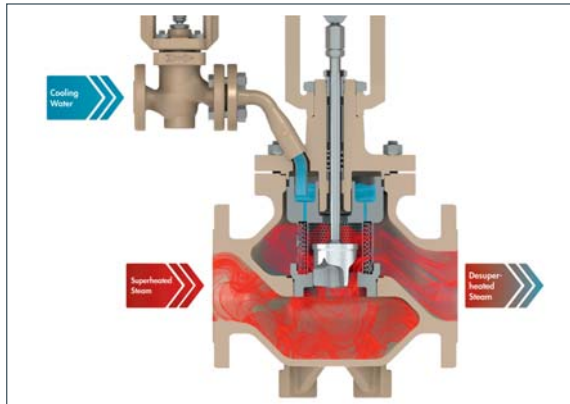


Fig. 7: The SAMSON steam-conditioning valve

The SAMSON steam-conditioning valve has a unique design that injects the cooling water directly at the outlet of the vena contracta into a special device known as a flow divider, which consists of solid metal inner and outer cages and an internal wire mesh system. By using a flow divider, the steam comes into contact with the cooling water at its maximum velocity at the inner edge of the flow divider. This helps achieve a very high Weber number and thus excellent water atomization. The very fine water droplets created are further reduced in size after passing through the wire mesh system in the flow divider. Furthermore, the velocity of the steam at the vena contracta is independent of the steam flow rate, which allows the SAMSON steam-conditioning valve to achieve the maximum possible steam and water turndown ratios, limited only by the pipeline velocity limits downstream of the valve. The flow divider also creates an extra steam pressure letdown stage, which means that internal sound pressure levels and system vibration are minimized.

The steam-water mixture exits the flow divider as a thin fog with very small water droplets remaining, which minimizes evaporation time and ensures that the water is distributed evenly across the entire cross-sectional area of steam flow. This also allows the system to achieve outlet temperatures very close to saturation.

To avoid thermal stress between the cooling water and superheated steam, the injected water is first intro-

duced into the valve through an internal sleeve not in contact with the valve body, which protects the water flange connection from any possible thermal stress. Additionally, the fine water dispersion from the flow divider ensures that no large water droplets come into contact with the valve body or downstream pipe walls.

Typical applications

The SAMSON steam-conditioning valve can be found in almost every major industry, including chemical and petrochemical, pulp and paper, food and beverage, oil refining, sugar refining, heat supply stations, and textiles. In the following two sections, the functioning of steam-conditioning valves in process plants and heat supply stations is described.

Steam-conditioning valves in process plants

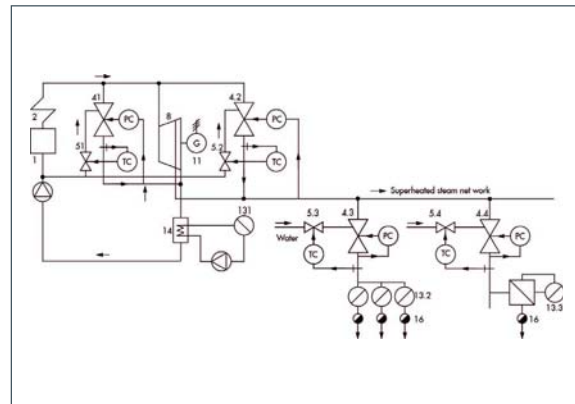


Fig. 8: Steam-conditioning valve in the bypass of an uncontrolled extraction condensing turbine and for supplying different consumers

It is quite common for many factories and process plants to have one or more superheated steam ring lines to supply consumers with thermal energy. As the heat must be distributed over long distances, which means temperature losses, these systems are supplied with superheated steam. Superheated steam arrives at the consumer, where it must be converted to steam at a specific pressure and temperature. An uncontrolled extraction condensing turbine is one example of supplying steam to the various networks. A basic circuit diagram of such a system is shown in Fig. 8, where only one extraction is shown for clarity.

As it is shown in the flow diagram, several steam-conditioning valves are installed throughout the plant. The steam-conditioning valves (4.1 and 4.2) operate as turbine bypass valves. They ensure a sufficient energy supply to the consumer group (13.1) and the superheated steam network. This central superheated steam network is used to supply the different consumers. Optimum utilization of thermal energy is achieved only when each consumer is supplied with saturated steam having the temperature required for the respective process. In the diagram, consumer groups requiring the same temperature as for example 13.2 have their own steam-conditioning valve.

The steam-conditioning valve 4.4 in Fig. 8 supplies heat exchangers for indirectly connected consumers (13.3); valve 4.3 supplies directly connected consumers, such as chemical reactors, distilling columns, driers, boilers, and similar equipment.

Steam-conditioning valves in heat supply stations

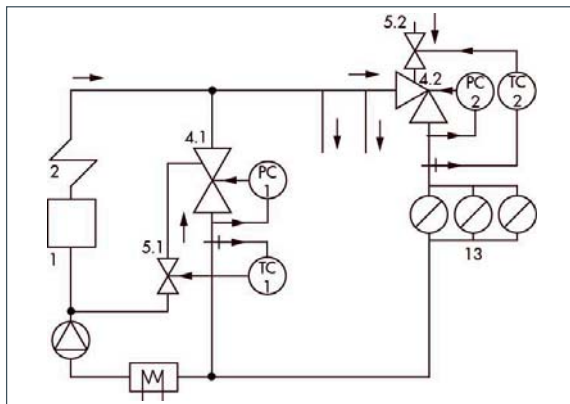


Fig. 9: Steam-conditioning valves in a heat supply station with consumers connected in series

Fig. 9 shows a basic diagram of a heat supply station, which generates thermal energy needed for district heating supply, heating, or process steam. The steam-conditioning valve (4.1) ensures a constant steam condition in the supply network. If the demand for heat and steam decrease, e.g. due to an unexpected shutdown of consumer groups, the steam boiler cannot respond immediately to such instantaneous load changes and more steam than necessary is generated. This means that an excess pressure is created in the

pipework between the superheater (2) and the consumers unless the steam-conditioning valve discharges the excess steam, thus reducing pressure and temperature to safe levels in the return flow pipe to the condenser.

As a result, the steam-conditioning valve (4.1) ensures that the excess steam which is produced for a short time is not relieved through a safety valve, that the plant is protected against excessive pressure and temperature, and that the consumers are not supplied with steam in an unacceptable state at any time. The steam-conditioning valve (4.2), which controls the hot steam from the boiler (1) with superheater (2) to the necessary values, is assigned to the consumer group (13).

Conclusion

Each type of desuperheating system has specific applications it is best suited for. When only the steam temperature needs to be reduced while maintaining a constant operating pressure, a nozzle-style desuperheater is the best option. When both the steam temperature and pressure need to be reduced, a SAMSON steam-conditioning valve can provide the following benefits:

- Maximized steam and water turndown ratios to cover all necessary load cases.
- Achieves steam temperatures very close to saturation temperature, thus optimum use of the thermal energy.
- Compact design that can also minimize the straight pipe length required downstream of the valve.

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