Open Access Journal
Modern Engineering 1 (2023) 24-32
journal homepage: https://mengineering.eu/

The Usage of Self-Regulating Steam Traps for Optimal Condensate Removal in Steam Pipelines

Andrzej GRZEBIELEC *[1], Adam SZELĄGOWSKI[1], Mateusz ŚMIECHOWICZ[2], Michał STĘPIEŃ[2]

[1] Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Heat Engineering, Warsaw, Poland
[2] Eneon sp. z o. o., Warsaw, Poland

Abstract

In energy-intensive systems, in which energy need to be transported through compact pipelines, steam is very often used as an energy carrier. The latent heat of steam condensation, surpassing its sensible heat, presents a distinctive advantage, resulting in steam pipelines requiring diameters significantly smaller compared to those needed for equivalent thermal power transmission. Nonetheless, the insulation of steam pipelines remains imperfect, resulting in inevitable heat dissipation. Consequently, this thermal loss leads to the condensation of water within the pipelines, necessitating the implementation of steam traps. The precise selection and implementation of suitable steam traps are essential for sustaining optimal pipeline functionality while minimizing energy losses. This research endeavors to comprehensively assess the criteria governing steam trap selection, focusing on their pivotal role in facilitating efficient pipeline operation. To achieve this objective, a mathematical analysis was conducted to quantify the volume of liquid generated within the pipeline due to condensation. Subsequently, an innovative self-regulating steam trap was introduced and evaluated to elucidate its efficiency in evacuating the accumulated liquid. Remarkably, the utilization of these advanced self-regulating steam traps yielded remarkably positive outcomes, profoundly enhancing pipeline performance and obviating steam losses. Through meticulous analysis of the mathematical model and empirical validation of the novel steam trap's functionality, this study not only contributes to enhancing the theoretical understanding of steam pipeline dynamics but also offers practical insights into optimizing their operational efficiency. This research showcases the potential of self-regulating steam traps to revolutionize steam pipeline dewatering practices, ensuring sustained energy transmission with minimal wastage and reaffirming their pivotal role in modern energy systems.

Keywords: steam pipelines, pipeline efficiency, steam traps, energy efficiency.

1. Introduction

Steam traps are used wherever steam losses must be controlled, and at the same time, too much condensate must not be allowed to accumulate. Despite the fact that the devices have the word "steam" in the name, condensate usually flows through them. The main applications of steam traps are [1,2,8]:

- dewatering of steam pipelines;
- control of operation of heat exchangers (steam condensers);
- dewatering of steam turbines;

On the other hand, traps, due to the principle of operation, are divided into [1, 6, 9]:

- thermostatic traps:
    - pressure-steam – opening or closing of the closing body is caused by an imbalance between the pressure of the condensate in the trap and the vapor pressure of the easily evaporating liquid contained in the deformable element (balanced pressure)

* **Corresponding author:** E-mail address: (andrzej.grzebielec@pw.edu.pl) Andrzej GRZEBIELEC

Received 4 December 2022
Available online 15 March 2023
ISSN 2450-5501
Published by Centrum Rzeczoznawstwa Budowlanego

- bimetallic or thermoelastic - opening or closing of the closing body depends on the deformation of the bimetallic or thermoelastic element, which depends on the changing temperature of the incoming condensate (bimetallic)
- liquid or solid expansion – opening or closing of the closing body depends on the temperature change of the condensate acting on the element with a high coefficient of thermal expansion.

- thermodynamic traps:
  - steam traps with an unbalanced closing body - pressure differences between the inlet and the pressure chamber cause the closing body to open or close.
  - impulse traps - pressure differences between the inlet and the pressure chamber cause the opening or closing of the closing body (piston slide)
  - labyrinth or orifice traps - liquids flow freely through the orifice. Condensate can eliminate or reduce the flow of water vapor or non-condensable media.
- mechanical traps:
  - traps with a closed float - opening or closing of the closing element is caused by a change in the condensate level in the trap housing.
  - traps with an open float - opening or closing of the closing body is caused by a change in the condensate level in the float.
  - traps with an open inverted float - opening or closing of the closing body is caused by a change in the level of condensate in the float (also called bell traps).

2. Steam pipelines

When steam flows through steam pipelines, water condenses as a result of heat transfer from the outside of the pipeline to the outside. As a result, every specified section of the L_{st} pipeline, a trap must be installed to drain the condensed liquid. Traps should also be installed [11,12,13]:

- Upstream of reducing valves
- Through shut-off valves
- In front of heavy automation components, they can generate condensation
- In depressions of pipelines.

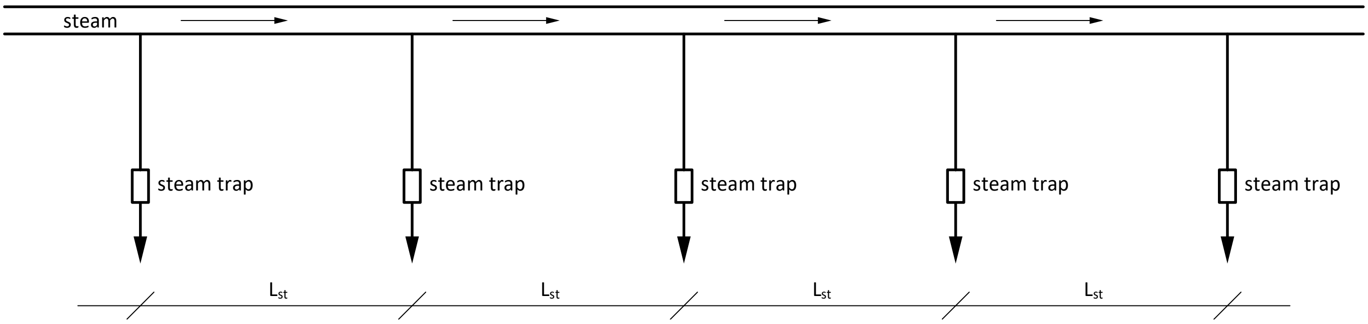

Figure 1. Steam trap mounted on steam pipelines

Figure 1 shows an example of steam trap installation on a steam pipeline. The distance between traps depends on a number of factors: pipeline diameter, insulation thickness, steam flow.

2.2. Heat loss in the steam pipeline

Diagram 2 shows a section of the steam pipeline. The main pipe is usually made of carbon steel, the entire pipeline is insulated with mineral wool. In order to keep the pressure loss at a reasonable level, it is recommended that the steam velocity does not exceed 25 m/s [7].

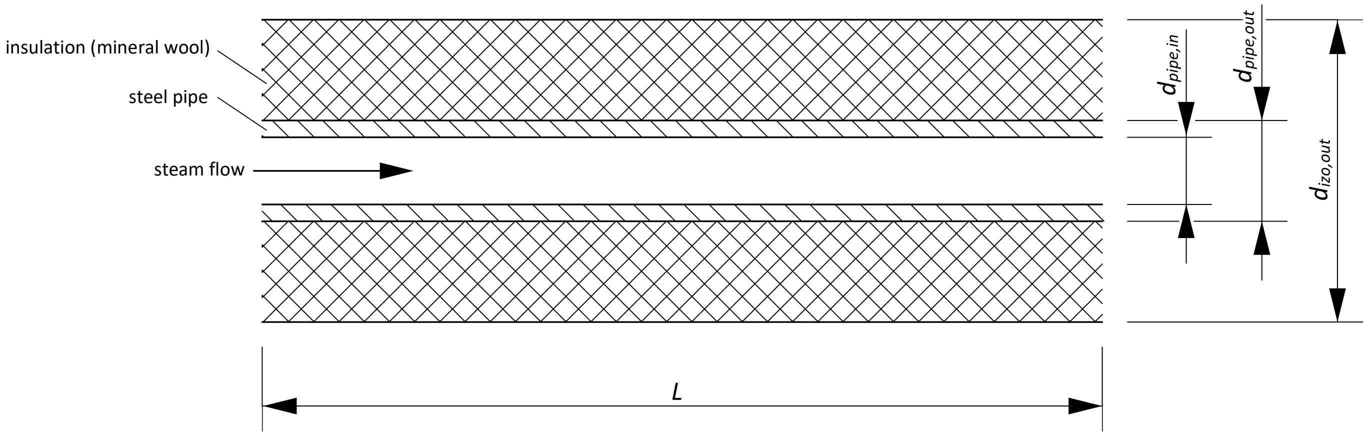

Figure 2. Steam flow in the pipeline

For the geometry shown in the diagram 2, it can be described

$d_{pipe,in}[m]$ - inner diameter of steel pipe;

$d_{pipe,out}[m]$ - outer diameter of steel pipe;

Since the outer diameter of the pipe is the inner diameter of the insulation, the relation can be written

$$d_{izo,in} = d_{pipe,out}[m] \tag{1}$$

and based on the input parameter, which is the thickness of the h_{izo} insulation, it can be also possible to determine the outer diameter of the insulation:

$$d_{izo,\mathrm{out}} = d_{izo,\mathrm{in}} + 2 \cdot \mathrm{h_{izo}}[m] \tag{2}$$

To determine the condensate stream that will appear during the flow, the following heat transfer relationships for pipe partitions should be used [3,4]:

$$q_{l,out} = \frac{\pi \cdot \left(T_{izo,out} - T_a\right)}{\frac{1}{\alpha_{out} \cdot d_{izo,out}}} \left[\frac{\mathrm{W}}{\mathrm{m}}\right] \tag{3}$$

$$q_{l,izo} = \frac{\pi \cdot \left(T_{izo,in} - T_{izo,out}\right)}{\frac{1}{2 \cdot \lambda_{izo}} ln\left(\frac{d_{izo,out}}{d_{izo,in}}\right)} \left[\frac{\mathrm{W}}{\mathrm{m}}\right] \tag{4}$$

$$q_{l,pipe} = \frac{\pi \cdot \left(T_{pipe,in} - T_{izo,in}\right)}{\frac{1}{2 \cdot \lambda_{cs}} ln\left(\frac{d_{izo,in}}{d_{pipe,in}}\right)} \left[\frac{\mathrm{W}}{\mathrm{m}}\right] \tag{5}$$

(6)

$$q_{l,in} = \frac{\pi \cdot (T_{sat} - T_{pipe,in})}{\frac{1}{\alpha_{in} \cdot d_{pipe,in}}} \left[\frac{\mathrm{W}}{\mathrm{m}}\right]$$

where

$q_{l,in}$	$\left[\frac{W}{m}\right]$	linear heat flux density on the side of the condensing steam;
$q_{l,pipe}$	$\left[\frac{W}{m}\right]$	linear density of the heat flux flowing through the pipe in which the steam flows (carbon steel pipe);
$q_{l,izo}$	$\left[\frac{W}{m}\right]$	linear density of the heat flux flowing through the insulation of the pipeline;
$q_{l,out}$	$\left[\frac{W}{m}\right]$	linear density of the heat flux flowing from the pipeline to the environment
T_a	[°C]	The temperature of the air surrounding the pipeline
$T_{izo,out}$	[°C]	Temperature on the surface of the insulation
$T_{izo,in}$	[°C]	The temperature on the inner surface of the insulation is also the temperature on the outer side of the pipe in which the steam flows
$T_{pipe,in}$	[°C]	The temperature at the inner surface of the pipe in which the steam flows
T_{sat}	[°C]	Saturation temperature
λ_{izo}	$\left[\frac{W}{m \cdot K}\right]$	The thermal conductivity of the insulation material
λ_{cs}	$\left[\frac{W}{m \cdot K}\right]$	The thermal conductivity of the pipe material;
α_{out}	$\left[\frac{W}{m^2 \cdot K}\right]$	Heat transfer coefficient between the outer layer of insulation and the outside air;
α_{in}	$\left[\frac{W}{m^2 \cdot K}\right]$	Heat transfer coefficient between the inner surface of the pipe and the steam;

In steady state, all the listed linear heat fluxes should be equal to each other:

$$q_{l,in} = q_{l,pipe} = q_{l,izo} = q_{l,out} \left[\frac{\mathrm{W}}{\mathrm{m}}\right] \tag{7}$$

Unfortunately, in the eqations set there is more unknowns than equations (exactly one more) - so the system must be solved iteratively. Assuming one parameter at the beginning of the calculation. In this example We assume the outer wall of the insulation $T_{izo,out}$ will be assumed as (for the first step of iteration):

$$T_{izo,out} = T_a + 5[°\mathrm{C}] \tag{8}$$

From the air side (external side), the heat transfer coefficient is defined by the relation

$$\alpha_{out} = Nu_a \frac{\lambda_a}{d_{izo,out}} \left[\frac{W}{m^2 \cdot K}\right] \tag{9}$$

where

Nu_a	$[-]$	Nusselt number, for air side convection;
λ_a	$\left[\frac{W}{m \cdot K}\right]$	Thermal conductivity of air

The Nusselt number, in turn, is calculated from the dependence

$$Nu_a = 0{,}135(Pr_a \cdot Gr_a)^{1/3}[-] \tag{10}$$

where

Pr_a	$[-]$	Prandtl number for air
Gr_a	$[-]$	Grashof number for air;

$$Pr_a = \frac{c_{p,a} \cdot \eta_a}{\lambda_a}[-] \tag{11}$$

where

$c_{p,a}$	$\left[\frac{J}{kg \cdot K}\right]$	The specific heat of the air
η_a	$[Pa \cdot s]$	Air dynamic viscosity

$$Gr_a = \frac{g \cdot (d_{izo,out})^3 \cdot \beta_a \cdot \left(T_{izo,out} - T_a\right)}{\nu_a^2}[-] \tag{12}$$

where

$g = 9{,}81$	$\left[\frac{m}{s^2}\right]$	Gravitational acceleration
β_a	$\left[\frac{1}{T}\right]$	Air thermal expansion coefficient
ν_a	$\left[\frac{m^2}{s}\right]$	Kinematic viscosity of air

$$\beta_a = \left|\frac{1}{\rho_a(T_a - 0{,}5)} - \frac{1}{\rho_a(T_a + 0{,}5)}\right| \left[\frac{1}{\mathrm{K}}\right] \tag{13}$$

$$\nu_a = \frac{\eta_a}{\rho_a}\left[\frac{m^2}{s}\right] \tag{14}$$

On the other hand, the heat transfer coefficient on the side of the condensing steam is determined according to the following formula:

$$\alpha_{in} = 0{,}728\left(\frac{\lambda_w^3 \cdot \rho_w \cdot (\rho_w - \rho_v) \cdot g \cdot h_{fg}}{\eta_w \cdot d_{pipe,in} \cdot (T_{sat} - T_{pipe,in})}\right)^{0.25}\left[\frac{W}{m^2 \cdot K}\right] \tag{15}$$

where

λ_w	$\left[\frac{W}{m \cdot K}\right]$	Water thermal conductivity coefficient for wall temperature
ρ_w	$\left[\frac{kg}{m^3}\right]$	Water density for wall temperature
ρ_v	$\left[\frac{kg}{m^3}\right]$	Vapor density for steam pressure
h_{fg}	$\left[\frac{J}{kg}\right]$	Heat of phase change for known vapor pressure
η_w	$[Pa \cdot s]$	Dynamic viscosity of water for wall temperature
T_{sat}	[°C]	Steam saturation temperature for known pressure

At the end of the iteration process, it is possible to obtain a linear heat flux $q_{l,in}\left[\frac{W}{m}\right]$. And knowing this value, it can be calculated what will be generated linear stream of condensate inside the steam pipeline

$$\dot{m}_{l,c} = \frac{q_{l,in}}{h_{fg}}\left[\frac{kg}{s} \cdot \frac{1}{m}\right] \tag{16}$$

3. Proposed self-adjusting steam trap

As part of the project, a novel type of steam trap was designed and built. Self-regulation is based on the flow characteristics of the steam trap [5, 10, 14].

Photo 3. Novel steam trap

Picture No. 3 shows the view of the pre-designed steam trap, and Diagram 4 shows the characteristics of the water stream change depending on the subcooling temperature. The subcooling temperature is the temperature difference between the saturation temperature for the pressure of the steam and the measured condensate temperature.

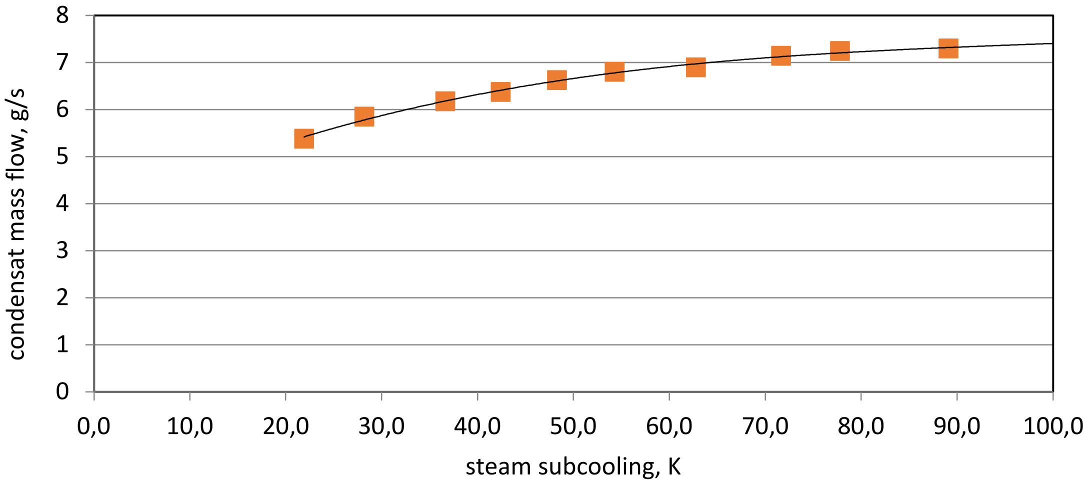

Figure 4. Condensate mass flow for a proposed steam trap as a function of subcooling value

According to diagram No. 4, it can be seen that when the subcooling of the condensate is greater, the stream of the flowing liquid is also greater, when the subcooling decreases, the stream also decreases. In practice, this should be interpreted as follows. As more liquid is formed in the steam line, the temperature of that liquid decreases towards the ambient temperature. Which means that the subcooling temperature is increasing. Thus, the flow increases. A larger stream discharges more liquid, so less liquid remains in the pipeline. This, in turn, reduces the supercooling of the liquid - and thus the flux begins to decrease. Therefore, it is very important to select the appropriate size of the trap as well as the selection of the distance between successive traps.

4. Analyzed system

For the analysis, a 4 km steam pipeline was adopted, the purpose of which is to supply 4 MW of heat to an industrial plant, its external diameter is 200 mm, and the insulation is made of mineral wool. Traps on steam pipelines are installed in such a way that they are drawn from the relevant pipelines, which will determine the distance down the pipe, through which the condensate flows by gravity. At the end of the tubes there are steam traps. In standard solutions, an analysis of how often steam traps should be performed is very rarely carried out - and steam traps, e.g.

mechanical float traps, are used. What contributes to the losses on the pipeline and very often the traps pass the so-called live steam.

According to the model presented in the previous chapter, the amount of condensate appearing in the pipeline will depend on the outside temperature. Diagram No. 4 shows the flow of condensate per 1 m of the pipeline, depending on the ambient air temperature.

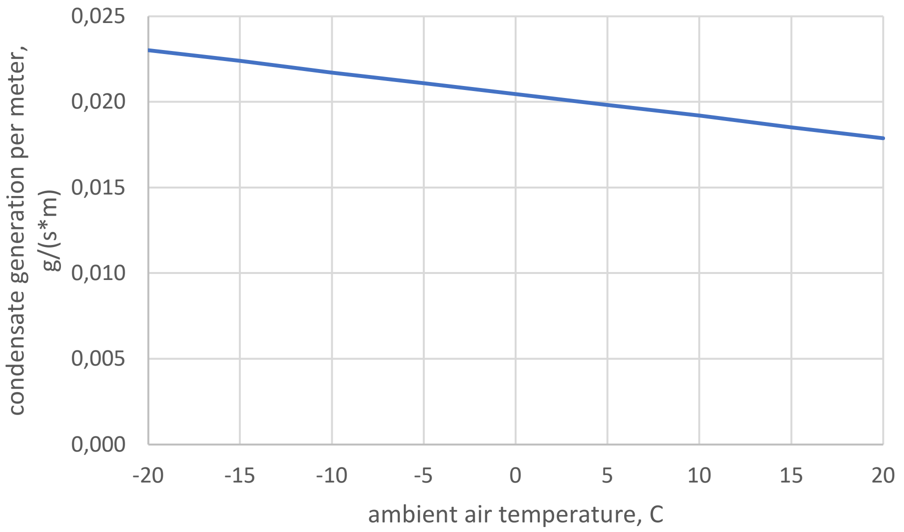

Figure 5. Condensate generation

This means that the lower the temperature, the more condensate there is to remove.

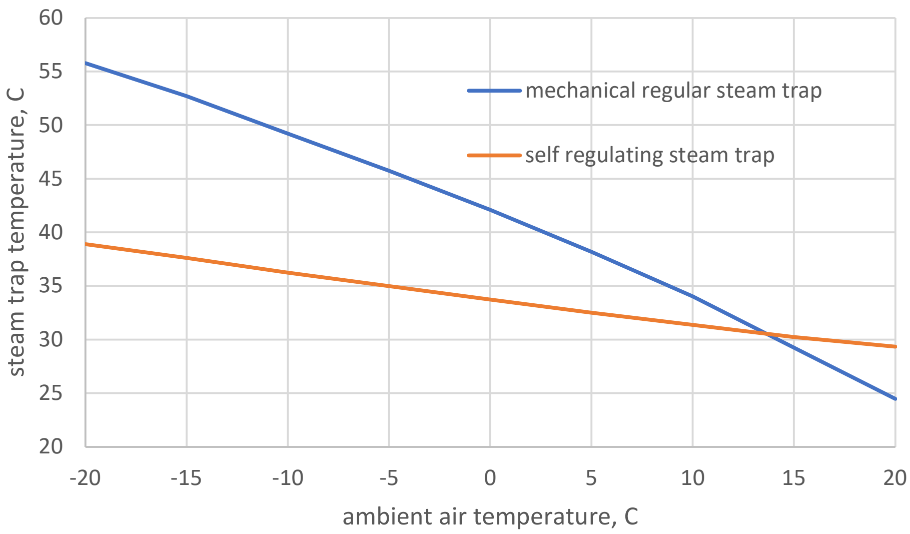

Figure 6. Steam trap temperature

After taking into account the change in the stream flowing through the trap, the temperature of the trap was determined (Fig. 6.). It can be seen that in the case of the proposed trap, the temperature will be lower, which in practice also means that this type of solution will generate lower losses in the pipeline. It should also be remembered that the temperature of the trap cannot be too low, as this may cause the water in them to freeze in the winter months. According to flow characteristic from Figure 4 and amount of condensate generated per one meter of pipeline it was determined that steam tramps should be installed every 300 m from each other.

5. Conclusions

The presented analysis shows that the new steam trap with characteristics adapting to external conditions performs much better than traditional traps. On the one hand, when the power demand of the process increases, the steam trap is able to discharge more condensate at a constant outside air temperature. Because in this case the temperature of the condensate will start to drop. On the other hand, when the temperature of the outside air drops, and thus the losses in the pipeline increase - and more condensate appears. The new steam trap is able to collect the condensate while keeping the temperature high enough – high enough that the condensate does not freeze. On the other hand, due to the change in characteristics, it does not cause an excessive increase in the temperature of the installation, and thus reduces heat loss through conduction.

Acknowledgments

This work was supported by the National Centre for Research and Development (Poland) [grant number: POIR.01.01.01-00-1259/17].

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