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Gas jet floatation for the touchless cooling of sensitive stainless steel strips in strip annealing lines

After the short description of the fundamentals of high convective gas jet cooling the application of this cooling technology in continuous stainless steel strip plants is illustrated. The jets caring for high heat transfer are simultaneously used for the stabilisation and the floating support of the strip. Even heavy strips of 2 mm thickness and more can be floated horizontally. Examples of executed cooling systems in production plants are shown.

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Introduction

The cooling is an essential part of the heat treatment of stainless steel strips. Strip cooling is required behind the annealing furnace in annealing and pickling or bright annealing lines. The furnaces are either vertical furnaces or furnaces in which the strip is guided in a catenarian curve and supported by rollers. These kinds of furnaces operate mostly with open combustion and an oxidising atmosphere. The cooling is - according to the design of the furnace - either vertical or horizontal. For a horizontal cooling system which is mostly operating with air jets scale particles sticking on support rollers can cause severe quality problems. Therefore, it is of advantage to support and stabilise the strip to be cooled floatingly with the cooling nozzles. For vertical cooling sections the cooling nozzles can be used to stabilise the strip effectively.

In some plants water cooling systems are installed. Especially for thin and wide strips water cooling which allows only limited control possibilities causes strong deformations because of the strong temperature gradient in the direction of strip run and the consequently rather sudden decrease of the strip width due to cooling.

In contrary to water cooling the gas jet cooling operates more gently avoiding these strong temperature gradients and sudden strip width decrease.

In the following the main important engineering aspects for the design of such cooling plants will be discussed and examples of high performance cooling plants will be demonstrated.

Heat transfer at gas jet cooling

The cooling effect is determined by the cooling speed

$$\frac{\Delta\vartheta}{\Delta t} = \frac{\alpha}{c \cdot \rho \cdot s}\left(\vartheta_{strip} - \vartheta_{gas}\right)$$

with

α = heat transfer coefficient
c = specific heat capacity of strip material
ρ = strip material density
s = strip thickness

For gas jet cooling even for relatively thick strip the temperature difference across the strip thickness can be neglected because the thermal conductivity of the strip material is relatively high. This is the case for strip thickness s = 6 mm and the maximum obtainable heat transfer coefficientin industrial plants with air cooling of about α = 300 W/m^{2}K.

For the conventional cooling gases – air in open cooling systems, nitrogen or hydrogen or a nitrogen/hydrogen mixture in closed systems – which can be considered as ideal gases, the similarity law of heat transfer

NU = f(Re)

can be written as a power law

$$Nu = \frac{\alpha \cdot l}{\lambda_{gas}} \sim \left(Re = \frac{c_{nozzle} \cdot l \cdot \rho}{\eta \cdot l}\right)^m \left(\frac{A_{nozzle}}{A_{total}}\right)^n$$

with

Nu = Nusselt number
Re = Reynolds number
l = characteristic dimension, i. e. strip-to-nozzle-distance
λ = thermal conductivity of the cooling gas
c_{nozzle} = gas velocity at nozzle exit
η = dynamic viscosity of the gas
ρ = gas density
A_{nozzle}/A_{total} = effective relative open nozzle area

The exponents, proven in numerous tests, are

$m \cong 0.7$ and $n \cong 0.4$.

From this equation follows

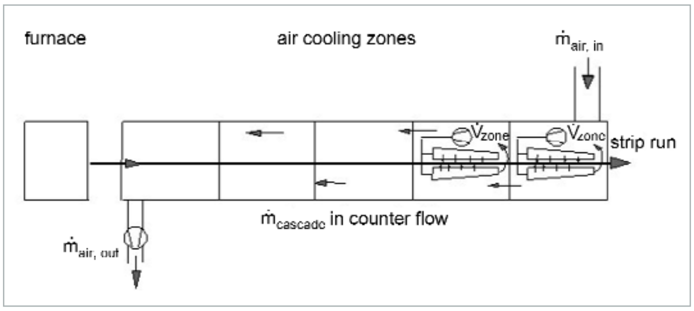

Fig. 1: Schematic of a cascade-cooling in an air jet floatation cooling plant for stainless steel strips

The heat transfer increases less than linearly with flow (and fan) speed

$a \sim c^{0.7}$

but it is well known that the fan power P_{fan} increases:

$P_{fan} \sim c^3$

So with the words of a businessman "you earn less than linearly but you pay with the 3rd power" → "bad business".

If an open air cooling is applied the gas properties are fixed. The only parameters available for a further optimisation are the scale of the system characterised by the length l and the relative open nozzle area A_{nozzle}/A_{total}. Large open area means large volume flow $\dot{V}$ of gas, which also means that a large gas mass flow is available for the heat exchange with the strip. Now the "cooling business" is better "you earn by the power of 0.4 but you pay only linearly" because

$P_{fan} \sim \dot{V}$

A "cost free" increase of heat transfer is possible by reducing the length l.

$\alpha \sim l^{-0.3}$

But the strip-to-nozzle-distances which are too small are critical from the plant operation point of view.

If a closed cooling system – under protective gas – is applied, a further increase of the heat transfer is possible by using hydrogen or a nitrogen/hydrogen mixture because the ratio

$$\frac{\lambda}{\eta \cdot \rho}$$

of the gas mixture is increased by the hydrogen content. But a significant increase of the heat transfer requires a hydrogen percentage for which the gas mixture becomes combustible. Therefore special safety means will be necessary.

An effective gas jet cooling system should be designed:

- for moderate gas speeds, e. g. gas nozzle pressures possible with simple industrial standard fans;
- for high – or better huge – gas flow;
- for strip-to-nozzle-distances not larger than necessary, what requires a rugged, stiff, and stable design of nozzles without protruding edges, pipes and "emergency rollers" integrated in the nozzle field in order to avoid strip contact even under extreme conditions.

A small scale of the cooling jet system furthermore means that the strip is cooled by a dense network of jet impingement points. For the design of the nozzle system it is important to obtain the highest possible arriving speed of the jet on the strip surface. This high arriving speed is obtained as long as the jet core comes still in touch with the strip surface.

Because of the high volume flow huge amounts of gas are circulated. In order to reduce the gas volume taken from the ambient and blown back into the ambient after having cooled the strip, WSP GmbH developed the so-called cascade-cooling principle (**Fig. 1**).

The cascade principle consists of several cooling zones arranged one behind the other. The air flow enters the last cooling zone and leaves the first cooling zone. So the gas flow is moved against the direction of the strip travel. The high heat transfer is obtained due to the fact that huge volumes of gas are recirculated in each cooling zone. So the heat transfer takes place in a cross counter flow situation. The heat balance is fulfilled by the counter flow and the heat transfer is fulfilled by the strong cross flow recirculation in each zone.

Due to the high volume flow recirculated another advantage is obtained, namely, a large ratio between the gas capacity flow and the strip capacity flow. Capacity flow means the product of mass flow x the specific heat capacity. A high capacity flow ratio between air and strip is the safest and cheapest way to avoid temperature differences which cannot be tolerated and which will lead - because of the different cooling over the strip width - again to strip planity problems.

Strip stabilisation by gas cooling jets

Because the cooling jet system is designed for large gas volume flow the cooling nozzles can also be used very effectively for strip stabilisation (**Fig. 2**). The Figure shows a schematic of a WSP stabilisation nozzle system. For simplification reasons the upper nozzles are not shown in the Figure. **Fig. 3** shows the pressure coefficient obtained on the strip surface vs. the floatation height which is the distance between strip and nozzle systems. The curve for the WSP nozzle system shows a significant increase of the floatation force with decreasing strip-to-nozzle-distance which corresponds to a rather stiff "gas spring". Such a stabilising system is not only suited for horizontal lines but also for vertical lines. In vertical lines there is

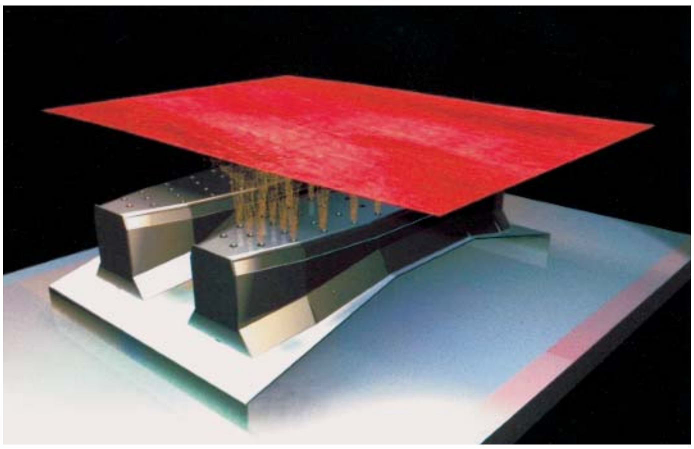

Fig. 2: Schematic of two lower floatation nozzles carrying a piece of sheet metal

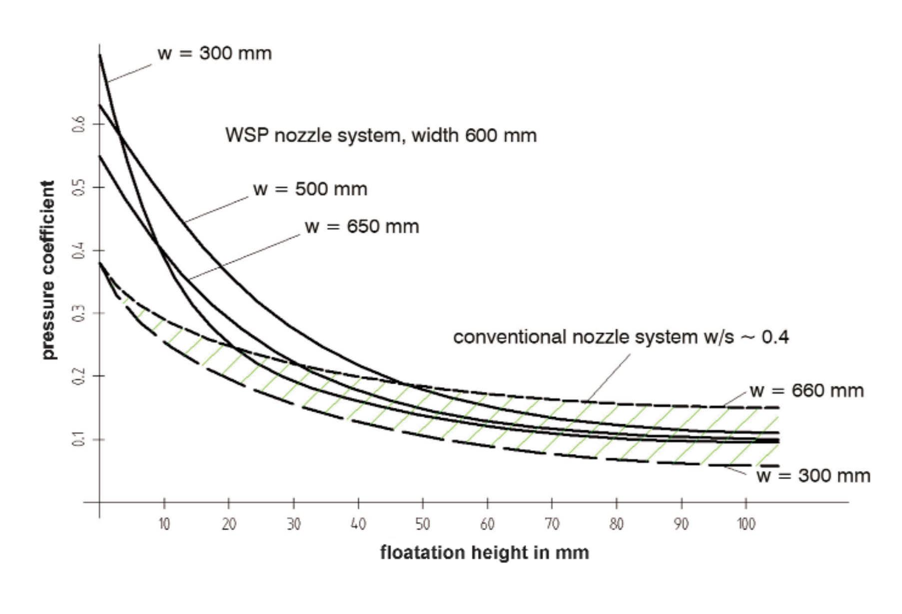

Fig. 3: Floatation pressure coefficient vs. floatation height for a bottom nozzle field

a problem of strip twisting if simple round jets are applied. The reason for this is that simple round jets will always de-stabilise the strip. If the strip is twisted the edges are closer to the nozzles and will be cooled faster than the centre part of the strip. Therefore floatation nozzles are needed for a good strip stabilisation which is the necessary precondition for a uniform cooling over the strip width in vertical lines, too.

Examples of cooling plants with floating strip

Fig. 4 is a view on the strip in a floatingly cooling plant behind a horizontal furnace in a cold strip line. The nozzle surface facing the strip is completely flat and has rounded edges.

The maximum strip width is 1.3 m. The strip thickness varies between 0.2 and 2 mm and the maximum throughput is about 50 to/h. The floatation section is about 40 m long and consists of 6 zones, 4 of which operate according to the cascade cooling principle. The entire cooling system is installed in a sound proof housing which allows perfect access by doors to each section.

Fig. 5 shows a similar plant especially designed for thin strips. In order to obtain a very flat strip, even at low strip thickness, the first section of the cooling plant (left) immediately behind the furnace is a so called "hot cooling zone".

The gas circulation in this hot cooling zone for the supply of the floatation nozzles is separated from the exchange of the fresh cooling air. One fan is installed for the fresh air supply and a second fan for the hot air exhaust. These two fans are operated thus that the continuity of air mass flow through the zone is guaranteed under all operating conditions. So the cooling gradient can be varied by the amount of fresh cooling air supplied to the zone without changing the floating behaviour. The hot cooling zone is "heated" by the strip and the operation temperature depends on the air flow which passes through the zone. The external wall of the hot cooling zones is thermally insulated. The maximum operation temperature is about 350 °C. This rather high air temperature reduces the temperature gradient in the temperature range where buckling of the strips can occur significantly.

Fig. 4: Strip floating in a cooling plant of a cold strip line

Fig. 5: Stainless steel strip floatation cooling plant with "hot cooling zone" behind the furnace