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Investigations of radiant tube arrangements and their effect on radiation exchange in horizontal furnaces

Dominik Büschgens *, Herbert Pfeifer

Department for Industrial Furnaces and Heat Engineering, RWTH Aachen University, Kopernikusstraße 10, Aachen, 52074, Germany

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ABSTRACT

Radiant tubes are highly stressed components, used to separate the atmosphere of the process from the combustion taking place inside the tube. For the identification of critical radiant tube positions in the furnace and possible life-time-promoting adjustments in the design and operation, consideration of the radiation exchange is essential. To address this problem, an already implemented and validated radiation modeling approach is used to determine the temperatures and heat fluxes of single-ended radiant tubes in a horizontal radiant tube furnace. The tube arrangement as well as the emissivities of the components were investigated with respect to their effect on the tubes' temperature, the furnace wall temperature and the heat flux on the strip.

It is shown that a horizontal distance of twice the radiant tube diameter between the tubes is optimal showing low and homogeneous temperatures on the tubes and the furnace wall as well as a homogeneous heat flux on the strip. For the vertical distance between tubes and the wall and between tubes and the strip, a value of half the tubes' diameter is found to be optimal. With this arrangement, the global temperature difference across a single tube does not exceed 67 K. The common installation recommendations for radiant tubes were reviewed and confirmed. It is also shown that misalignment of the tubes is not beneficial. The radiation exchange within the furnace is sensitive to the emissivities of the components, although it is clear that these can only be influenced to a very limited extent.

1. Introduction

Radiant tubes are a widely used component of thermoprocessing technology in furnaces of ferrous, non-ferrous and other industries. It is used to separate the non-oxidizing or protective gas atmosphere of the process from the combustion taking place inside the tube. Radiant tube furnaces are equipped with a large number of tubes of different geometries made of metal or ceramic [1]. Metallic tubes are typically used for the heat treatment of steel where furnace temperatures are in the range of 900 to 1100 °C [2]. With indirect heating, the tube temperatures are 100 to 150 °C above the furnace temperature [3]. Examples of such applications are continuous furnaces for hot-rolled strip annealing for high-quality grain-oriented and high-quality non-grain-oriented electrical strip, roller hearth furnaces in quenching and tempering lines for carbon steel plates, roller hearth furnaces for heat treatment in hot-form hardening applications, or horizontal non-oxidizing furnace for the hot dip galvanizing process [4]. Due to high thermal loads, radiant tubes are highly stressed components. In general, an annual failure rate between 10% and 20% can be assumed [5,6]. Not only is tube replacement costly, but production downtime and installation time must also be considered. This is the driving force behind the current efforts of radiant tube investigations in predicting lifetime and understanding the influencing parameters. The potential here lies in cost savings, but above all in predictive maintenance [7]. For the identification of critical radiant tube positions in the furnace and possible life-time-promoting adjustments in design and operation, consideration of radiation exchange is essential as it represents the dominant heat transfer mechanism at temperatures above 800 °C.

The radiant tube is the subject of several studies. Many of them have dealt with the operating conditions of the burner inside the tube [8,9]. Thermomechanical loads within the tubes caused by their temperature distributions are the subject of studies such as [10–14]. A more detailed example here are cyclic thermal loads caused, for example, by the frequently used intermittent operating mode of the burners and their influence on the radiant tube lifetime [15–18]. In addition to that, a radiant tube in the furnace is also exposed to temperature changes resulting from the heat exchange with the environment. This heat exchange takes place between the radiant tubes and the surrounding neighboring tubes, the furnace chamber, the furnace rollers and, above

* Corresponding author.
E-mail address: bueschgens@iob.rwth-aachen.de (D. Büschgens).

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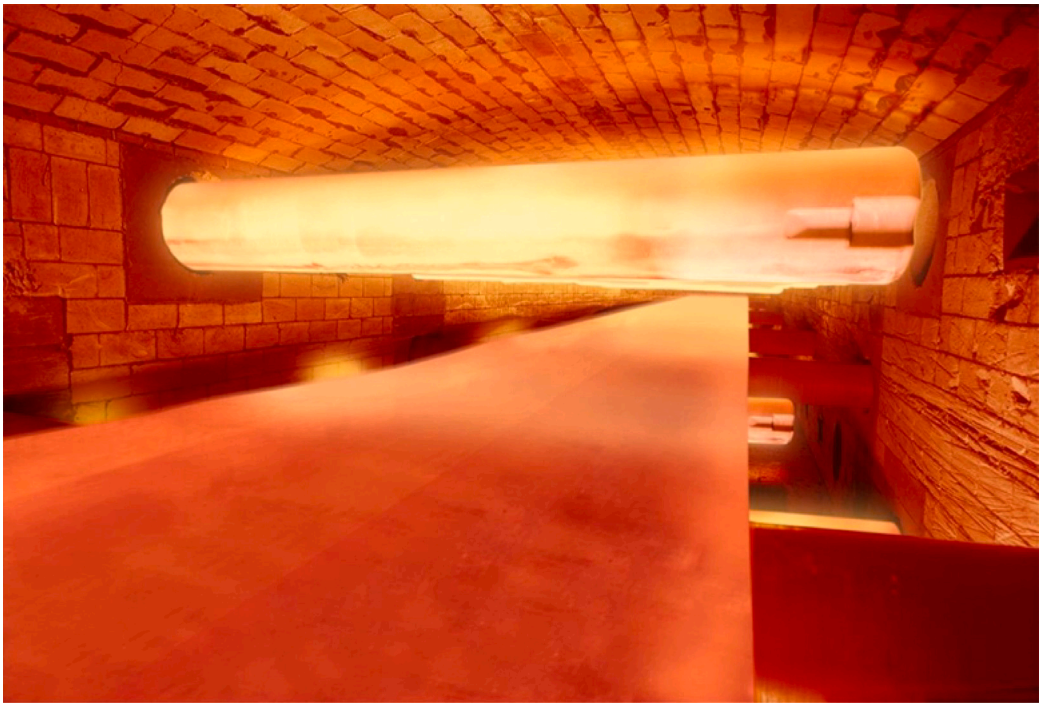


Fig. 1. View into a horizontal furnace with single-ended radiant tubes [24].

all, the passing strip. This surrounding radiation is strongly neglected in the available studies, leading to an isolated investigation of a single radiant tube. Previous investigations have already shown the significant influence of the surrounding radiation on the temperature distributions of the radiant tubes and the corresponding lifetime indicating parameters [19,20].

In addition to these studies, there are also common installation recommendations on the positioning of the radiant tubes in the furnace. In [21,22] it is stated that the distance between single-ended radiant tubes in a horizontal radiant tube furnace, Fig. 1, should be at least two times their diameter. Additionally, the distance between the radiant tubes and the furnace wall as well as the distance between the tubes and the strip are specified to be at least half the diameter of a radiant tube. The horizontal gap between the tubes enables radiation from the furnace wall towards the strip. With radiant tubes in close contact the furnace wall would be separated from the strip [23]. Besides the common installation recommendations, no other information with regard to the effects of the positioning for the heating of the strip or the temperature distributions on the components are given. The calculation data necessary for the comprehensibility of the data is not given.

Single-ended radiant tubes have been investigated both numerically and experimentally regarding the combustion taking place inside the tube [25,26]. Furthermore, there are approaches that cover the entire furnace in addition to focusing on combustion alone. When several radiant tubes were considered, the focus was usually on the temperature distribution of the heat-treated material. Gao et al. [27], for example, considered a roller hearth furnace for the heating of slabs with radiant tubes. A model of a furnace zone with 20 tubes was set up and validated with drag tests to determine the temperature of the slabs. The furnace zone model was coupled with an FVM model of a tube, which can also map the intermittent burner control. Rath et al. [28] developed a model to calculate the transient temperature profile of a product when it is conveyed through a roller hearth furnace based on view factors. The focus was on a model with reduced computational requirements, which could only be achieved through a simplified algorithm to calculate the shading within the radiation problem. All studies are based on a specific furnace geometry and therefore on one radiant tube arrangement. The arrangement itself and its effect on the radiation exchange within the furnace were not part of the investigations.

This work is focused on the positioning of single-ended radiant tubes in a horizontal radiant tube furnace for the heat treatment of steel strips, to generate a better understanding of the effect of positioning on the indicating parameters of radiant tube lifetime. At the same time, the findings are compared with the common installation guidelines and make the information traceable upon confirmation. Different variations of the horizontal distances between the tubes and the vertical distances between the tubes and the furnace wall as well as different distances between the tubes and the strip were investigated in order to find the ideal arrangement and therefore improve the design of the furnace. This work also goes beyond the state-of-the-art to examine arrangements that could be beneficial for the process, such as considering an offset of several tubes. The influence of different emissivities of the radiant tubes, strip, and furnace wall was also investigated. A homogeneous temperature distribution at low temperatures on the tubes and furnace wall, as well as a homogeneous heat flux distribution on the strip, are important factors in evaluating the ideal arrangement and are significant parameters for influencing the lifetime.

The results presented here can also be found in [29,30].

2. Radiation modeling

The already implemented and validated radiation model RadMod2D [31] is used to solve this two-dimensional radiation problem and determine the temperatures and heat fluxes occurring on the radiant tubes, the furnace wall and the steel strip in the radiant tube furnace. In contrast to other numerical models, which consider radiation only partially and simplified, this approach enables the accurate computation of two-dimensional radiation problems. Based on the radiation heat transfer of multiple surfaces in a closed space, view factors are used together with the net radiation method to calculate the exchanged heat fluxes between the geometries. This surface-to-surface approach can be used, as the atmosphere inside the furnace is not participating in the radiation exchange and, therefore, can be neglected. The investigations are based on a two-dimensional model of a horizontal radiant tube furnace for the heat treatment of steel strips. For modeling purposes,

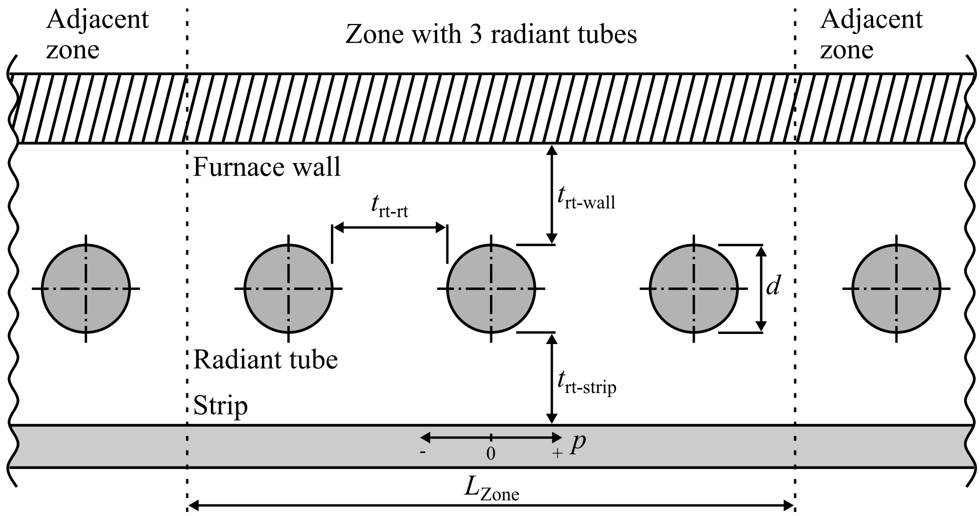


Fig. 2. Two-dimensional model of one zone with three radiant tubes of a horizontal radiant tube furnace according to [29,30].

the furnace is divided into zones of equal length, each equipped with three radiant tubes. A zone with two adjacent zones is shown in Fig. 2. The arrangement of the three radiant tubes in each zone is defined by the horizontal distance between the individual tubes $t_{\text{rt-rt}}$ as well as the distance between the radiant tubes and the furnace wall $t_{\text{rt-wall}}$ and the distance between the radiant tubes and the strip $t_{\text{rt-strip}}$. The radiant tubes used for this model have a diameter of $d_{\text{rt}} = 152\,\text{mm}$. The strip is positioned below the radiant tubes. Above the tubes there is the furnace ceiling or furnace wall.

The investigations are carried out with a zone in the middle of the furnace. This is necessary because of the hard to define boundary conditions at both ends of the furnaces, since the first and the last zones are influenced by the surroundings of the furnace e.g. other parts of the annealing line. The lower part of the furnace located below the strip with its transport system (rollers) and its additional radiant tubes are neglected.

The furnace wall and the radiant tubes are modeled with heat flux as their boundary conditions. For the strip a temperature boundary condition is used. As already stated, the boundary conditions at the first and last zones of the furnace are unknown. For this reason, a study was performed to determine the influence of the unknown boundary conditions on the evaluated zone in the middle of the furnace by determining the number of zones at which the boundary conditions no longer affect the middle zone. Calculations with several different numbers of zones, reaching from 3 zones up to 11, have been carried out and show that two zones on each side are required to eliminate any influence of the boundary conditions at either end of the furnace. This means that the model consists of 5 zones with a total of 15 radiant tubes. In addition to this, a mesh study has been performed with a variation in element size from $e = 0.0025\,\text{m}$ to $e = 0.03\,\text{m}$. Based on the results, an element size of $e = 0.01\,\text{m}$ is used for the following investigations.

All radiant tubes are modeled with an outgoing heat flux of $q_{\text{rt}} = 25\,\text{kW/m}^2$. This is based on typical power densities of metallic radiant tubes. The strip is assumed to have a constant temperature of $T_{\text{strip}} = 700\,°\text{C}$ along its length in the zone. The heat flux of the furnace wall results from the heat loss across the furnace wall to the surroundings. A typical heat loss of $q_{\text{wall}} = 1\,\text{kW/m}^2$ was estimated. The boundary conditions are shown in Table 1. The emissivities are based on [32,33], but changed for the emissivity study.

3. Results and discussion

The investigations were focused on the following points to determine the influence of the radiant tube arrangement on the radiation exchange within the furnace:

Table 1
Boundary conditions and emissivities of the parts of the model.

Component	Boundary condition	Emissivity
Radiant tube	$25\,\text{kW/m}^2$ (ingoing)	0.9
Strip	700 °C	0.6
Furnace wall	$1\,\text{kW/m}^2$ (outgoing)	0.9

- Investigation of the horizontal distance between the radiant tubes
- Investigation of the vertical distance of the radiant tubes to the furnace wall and the strip
- Investigation of a vertical misalignment of the central radiant tube
- Investigation of different emissivities of radiant tubes, strip and furnace wall

For all investigations, the influence of the different distances on the temperature distribution on the furnace wall and on the radiant tubes as well as the heat flux on the strip is determined. The temperature distribution on the radiant tube is plotted versus the angle φ of the tubes' circumference, where $\varphi = 90°$ reflects the closest point to the furnace wall and $\varphi = 270°$ reflects the closest point to the strip.

3.1. Horizontal distance between the radiant tubes

The first investigation focuses on the horizontal distance between the radiant tubes. To eliminate the influence of the vertical distance of the radiant tubes to the furnace wall and the strip, it is kept constant at $t_{\text{rt-wall}} = t_{\text{rt-strip}} = 0.5d$ for all calculations. The horizontal distances were varied between $0.5d \le t_{\text{rt-rt}} \le 5.0d$.

The temperature distribution across the central radiant tube is shown in Fig. 3. It can be seen that the point with the minimum distance to the furnace wall ($\varphi = 90°$) has the highest temperature. The point closest to the strip ($\varphi = 270°$) has the lowest temperature. With larger distances between the radiant tubes, the maximum and minimum temperatures are getting lower, as well as the temperature difference on the whole tube.

The heat flux on the strip is plotted in Fig. 4. The highest heat flux is observed for the smallest distance between the radiant tubes. Here, however, it is noticeable that the maximum and minimum shift with a change in the distance. At a distance of $t_{\text{rt-rt}} > 2.0d$, the maximum of the heat flux density distribution lies above the radiant tube. In contrast, at distances $t_{\text{rt-rt}} < 2.0d$, the minimum of the distribution is located at this position. The maximum is then located at the position of the previous

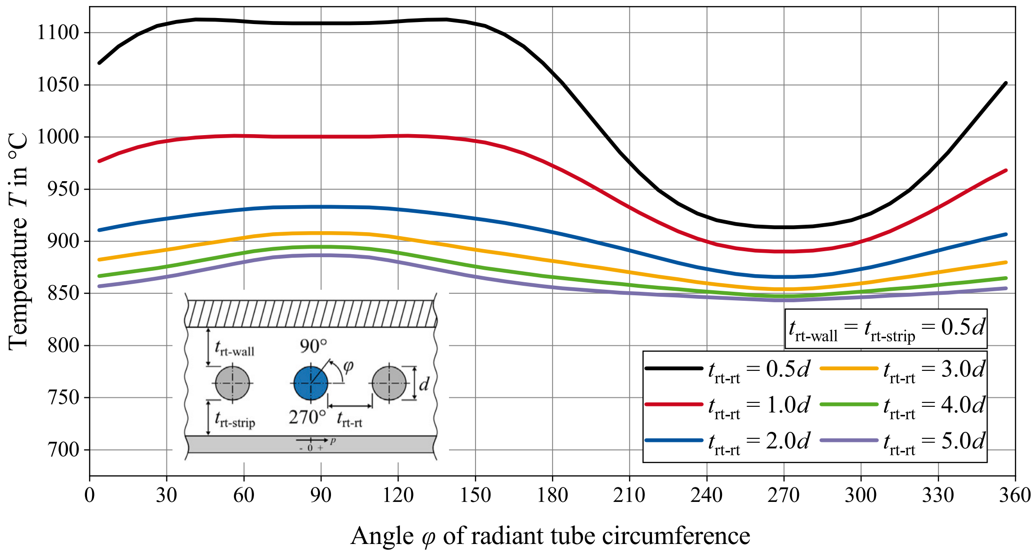


Fig. 3. Circumferential temperature distribution on the central radiant tube for different horizontal distances between the radiant tubes according to [29,30].

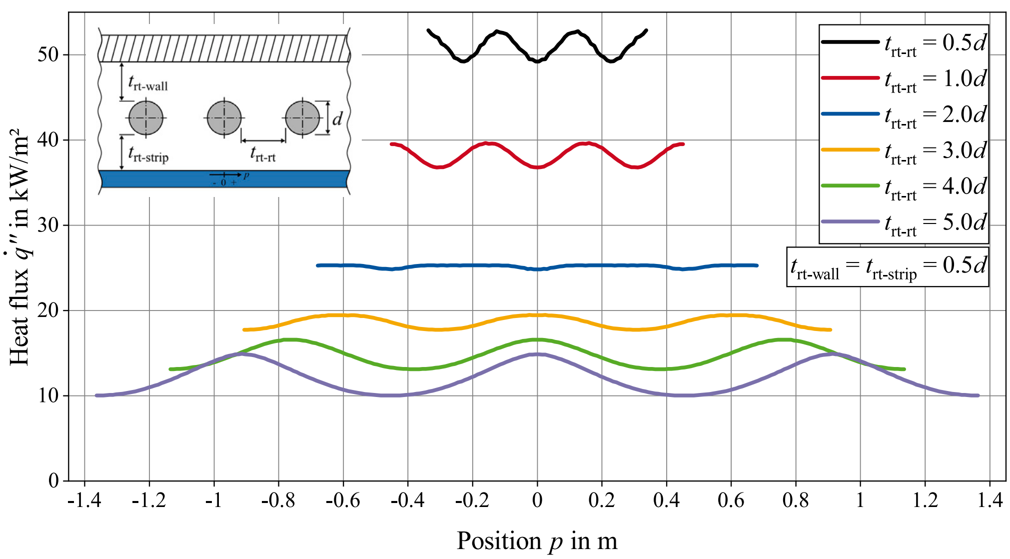


Fig. 4. Heat flux on the strip for different horizontal distances between the radiant tubes according to [29,30].

minimum exactly in the middle between two tubes. At a distance of $t_{\text{rt-rt}} = 2.0d$ the difference between the maximum and minimum heat flux is the smallest; in other words, the heat flux on the strip is the most uniform.

The temperature distribution for the furnace wall is shown in Fig. 5. The furnace wall temperature is observed to be significantly higher at small horizontal distances between the radiant tubes in comparison to larger distances. The positions of the radiant tubes are reflected in the temperature distribution by temperature maxima on the wall directly above the radiant tubes. It can be clearly seen for the central radiant tube at position $p = 0\,\text{m}$. Accordingly, the minimum temperature occurs in the middle between two radiant tubes.

The calculations can be used to derive an ideal horizontal distance between the radiant tubes. The goal is to achieve the most uniform heat flux onto the strip. At the same time, the thermal load on the furnace components such as the wall and the radiant tubes should be as low as possible. The maximum and average heat fluxes, Fig. 6(a), show that a distance of $t_{\text{rt-rt}} = 2.0d$ provides the most homogeneous heat flux along the entire length of the zone. It is noticeable that the length of the zone in this case is approximately equal to the sum of the circumferences of all three tubes located in the zone: $3U_{\text{rt}} = 3\pi d_{\text{rt}} \approx L_{\text{zone,2.0d}}$.

For the temperature distribution of the radiant tubes, Fig. 6(b), it can be deduced that a larger horizontal distance lowers the maximum temperature as well as the temperature gradient between the maximum and minimum temperature on the tubes. However, an optimum must be found between the resulting furnace length and the loads on the components. When comparing the temperatures at $t_{\text{rt-rt}} = 2.0d$ with those at larger distances, the difference becomes less significant.

A separate calculation with $t_{\text{rt-rt}} = (\pi - 1)d = 2.1415d$ shows that the average heat flux on the strip is exactly $q = 24\,\text{kW/m}^2$. For this specific radiant tube arrangement, the length of the zone corresponds to the sum of the circumferences of all three radiant tubes. This average heat flux results from the difference between the heat flux introduced through the radiant tubes and the heat flux discharged via the loss over the furnace wall. If the zone is somewhat shorter (here: $t_{\text{rt-rt}} = 2.0d$), this is reflected in a slightly higher mean heat flux.

In summary, it can be observed that a distance between the radiant tubes around $t_{\text{rt-rt}} = (\pi - 1)d$ leads to the most homogeneous heat flux on the strip. In addition, the temperature distributions on the furnace wall and the radiant tubes are in a moderate range, while still having a reasonable zone length. The results are in line with common installation

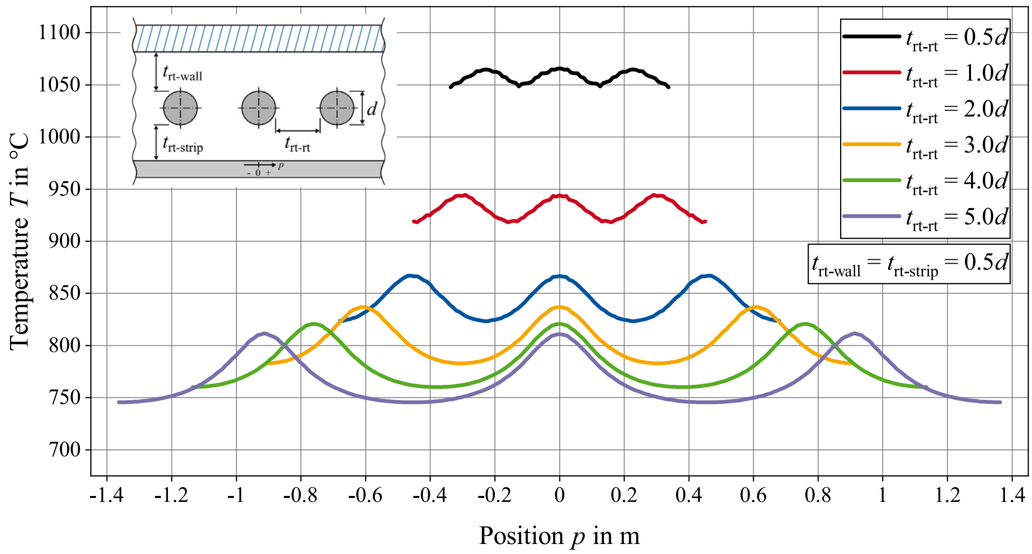


Fig. 5. Temperature distribution on the furnace wall for different horizontal distances between the radiant tubes according to [29,30].

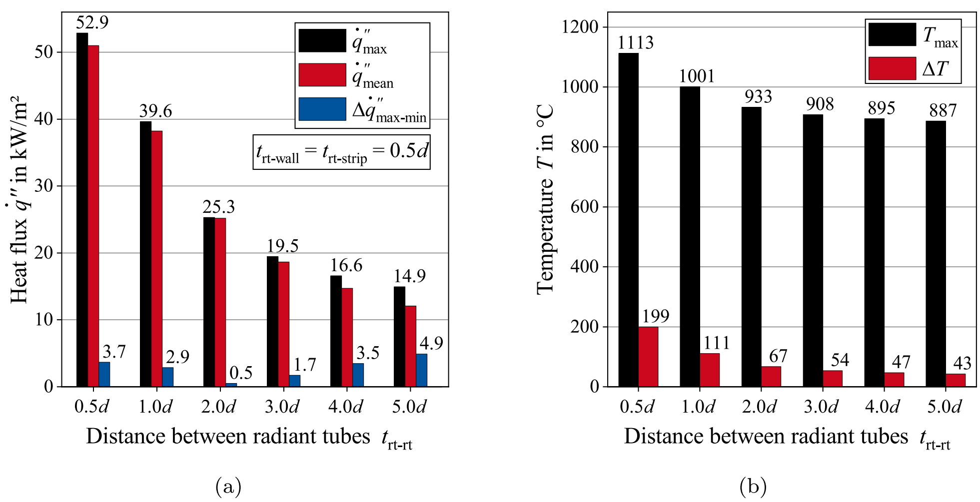


Fig. 6. Variation of the horizontal distance of the radiant tubes: Heat flux on the strip (a); temperature on the central radiant tube (b) according to [29,30].

practice. An investigation by Chmielowski [34] yields a similar result. However, other boundary conditions form the basis of the calculation.

Calculations were also carried out with even smaller distances $t_{rt\text{-}rt} < 0.5d$. In these cases, the resulting temperatures for the furnace wall and the radiant tubes are well above $T > 1500\,°C$. The use of metallic radiant tubes at these temperatures is not realistic. For this reason, only horizontal distances $t_{rt\text{-}rt} > 0.5d$ are shown in this study.

3.2. Vertical distance of the radiant tubes to the furnace wall and the strip

In addition to the horizontal distance $t_{rt\text{-}rt}$ between the radiant tubes, the influence of the vertical distance between the tubes and the furnace wall and the vertical distance between the tubes and the strip was investigated. The investigation was carried out in relation to the temperatures on the wall and tube as well as the heat flux on the strip. Both values $t_{rt\text{-}wall}$ and $t_{rt\text{-}strip}$ inevitably have an influence on the furnace height. The horizontal distance was kept constant at $t_{rt\text{-}rt} = 2.0d$ for the following investigations. Due to the increasing view factors of both furnace ends at larger furnace heights, their influence on the middle zone also increases. For this reason, the zone number is adjusted to $n = 11$. A variation of the distances $t_{rt\text{-}wall}$ and $t_{rt\text{-}strip}$ was carried out, where these two parameters were always kept equal ($t_{rt\text{-}wall} = t_{rt\text{-}strip}$) and applied in the same way to all radiant tubes.

The distribution of the temperature over the circumference of the central radiant tube shows the influence of the selected boundary conditions on the furnace wall and the strip, Fig. 7. The constant strip temperature does not cause a change in temperature at the bottom of the radiant tube ($\varphi = 180°$ to $\varphi = 360°$) with a larger vertical distance. However, on the top of the radiant tube ($\varphi = 0°$ to $\varphi = 180°$), the temperature changes significantly. The heat flux boundary condition of the furnace wall leads to an increase on the upper side of the tube facing the wall.

With higher distances between the radiant tubes and the strip, respectively, the furnace wall, the heat flux on the strip becomes more homogeneous, Fig. 8. At large distances of $t_{rt\text{-}wall} = t_{rt\text{-}strip} \geq 2.0d$ the heat flux is quite uniform throughout the length of the strip. If the distances are smaller, minima form above the radiant tubes ($t_{rt\text{-}wall} = t_{rt\text{-}strip} = 0.5d$ to $t_{rt\text{-}wall} = t_{rt\text{-}strip} = 1.5d$). At even smaller distances $t_{rt\text{-}wall} = t_{rt\text{-}strip} < 0.5d$, the location of the minimum shifts to the area between two adjacent radiant tubes. The smallest distance $t_{rt\text{-}wall} = t_{rt\text{-}strip} = 0.1d$ shows a clear maximum above each radiant tube. Instabilities can be observed for these small distances, caused by the view factor calculation as the ratio of distance between the elements to element size decreases.

Not only does the radiant tube temperature increase as the vertical distances decrease, but also the wall temperatures increase. Fig.

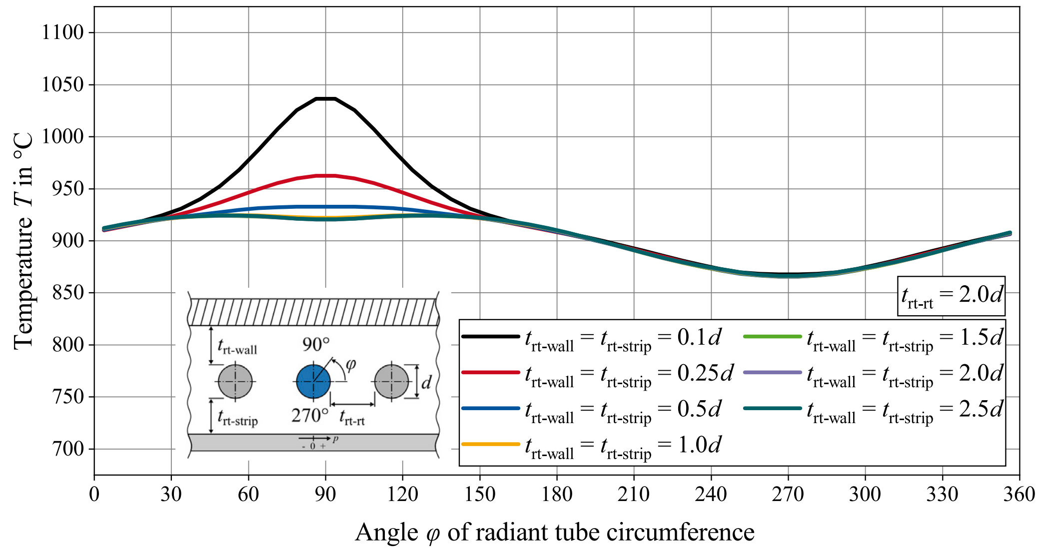


Fig. 7. Circumferential temperature distribution on the central radiant tube for different vertical distances between the radiant tubes and the furnace wall respectively the strip according to [29,30].

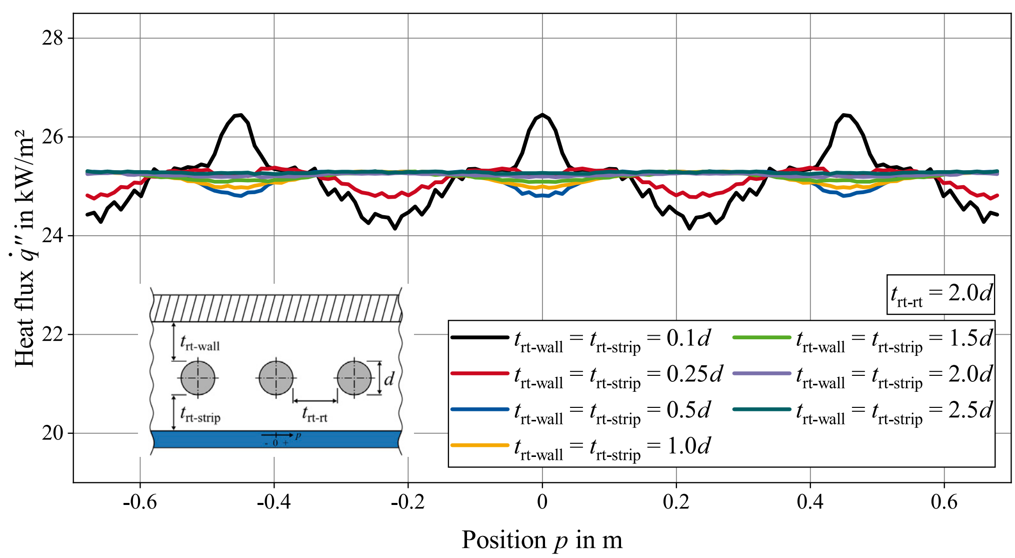


Fig. 8. Heat flux on the strip for different vertical distances between the radiant tubes and the furnace wall respectively the strip according to [29,30].

9 shows the temperature distributions on the furnace wall for the different vertical distances. The closer the radiant tubes are to the wall, the higher the wall temperatures that can be observed. At distances of $t_{\text{rt-wall}} = t_{\text{rt-strip}} \geq 1.5d$, a homogeneous temperature distribution can be seen on the wall.

Fig. 10(a) shows the mean heat flux of all vertical distances. It appears that they are almost identical for each calculation. Only the homogeneity changes, represented by the maximum heat flux and the difference to the minimum. The maximum radiant tube temperature and the gradients do not change significantly at a distance of $t_{\text{rt-wall}} = t_{\text{rt-strip}} = 1.0d$ or higher, Fig. 10(b).

A vertical distance of $t_{\text{rt-wall}} = t_{\text{rt-strip}} = 0.5d$ represents a good compromise between the necessary furnace height and the corresponding temperatures on the furnace walls and on the radiant tubes. At the same time, a relatively homogeneous heat flux can be observed on the strip. The larger distances and the resulting larger furnace heights do not show any significant benefit. The value of $t_{\text{rt-wall}} = t_{\text{rt-strip}} = 0.5d$ is found in common installation recommendations for radiant tubes in horizontal annealing lines.

3.3. Misalignment of the central radiant tube

The third investigation deals with a misalignment of the central tubes of each zone. The other two (right and left) radiant tubes in the zone are located centrally between the furnace wall and the strip at distances of $t_{\text{rt-wall}} = 1.0d$ and $t_{\text{rt-strip}} = 1.0d$. The central tube is misaligned to a position close to the furnace wall ($t_{\text{rt-wall}} = 0.5d$; $t_{\text{rt-strip}} = 1.5d$) and a position close to the strip ($t_{\text{rt-wall}} = 1.5d$; $t_{\text{rt-strip}} = 0.5d$). This is compared to a reference position ($t_{\text{rt-wall}} = 1.0d$; $t_{\text{rt-strip}} = 1.0d$). These three cases are depicted in Fig. 11.

All radiant tubes had the same temperature distribution in the previous investigations. However, if the central tube is no longer aligned with its two adjacent tubes, different temperature distributions occur. Fig. 12(a) shows the temperature distribution on all three tubes (left, central, right) with all tubes arranged in a horizontal line with the same distances to the strip and the furnace wall. This can be compared to the temperature distributions on the tubes with a misalignment and, therefore, an offset of the central tube in the direction of the furnace wall, Fig. 12(b), and in the direction of the strip, Fig. 12(c).

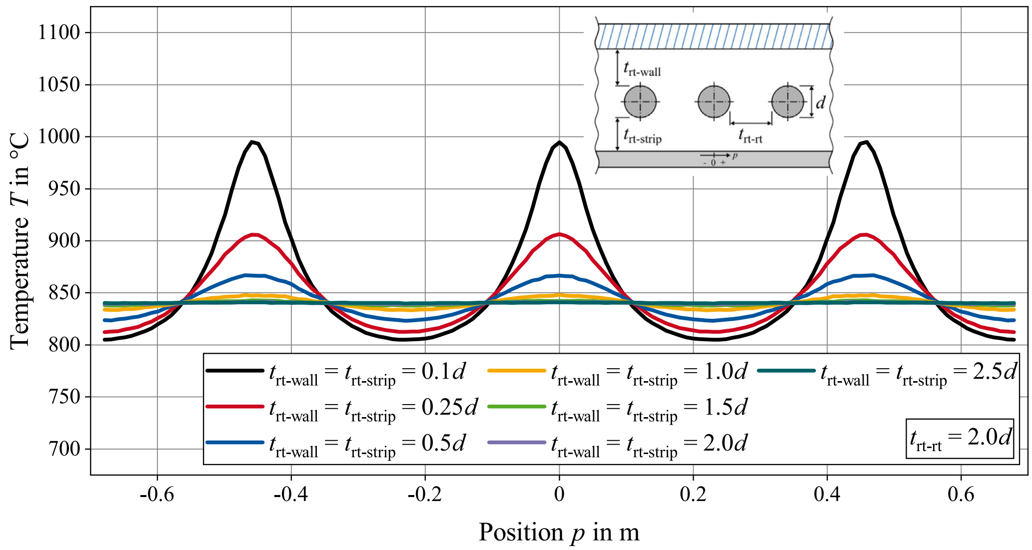


Fig. 9. Temperature distribution on the furnace wall for different vertical distances between the radiant tubes and the furnace wall and the strip according to [29,30].

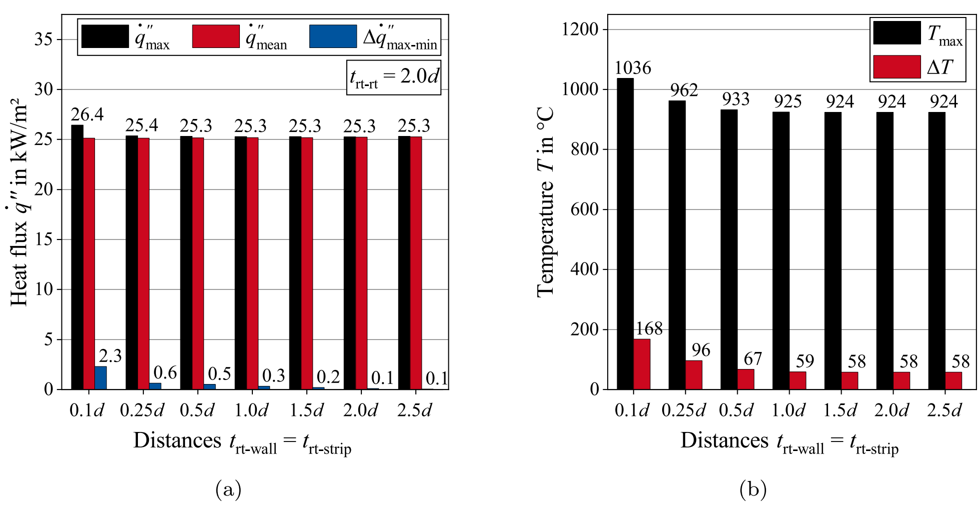


Fig. 10. Variation of the vertical distances of the radiant tubes to the furnace wall respectively the strip: Heat flux on the strip (a); temperature on the central radiant tube (b) according to [29,30].

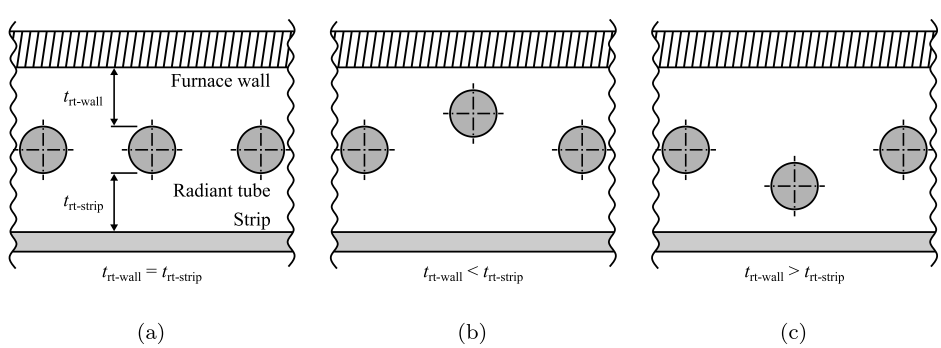
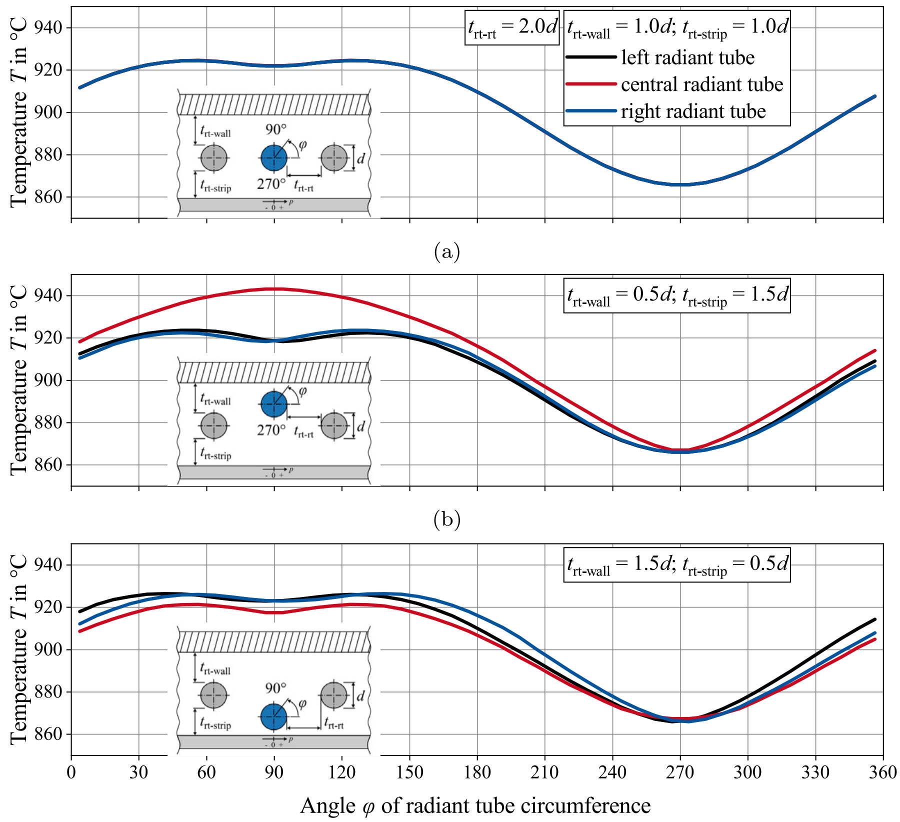


Fig. 11. Variation of the vertical distances of the central radiant tube: all radiant tubes aligned (a), central radiant tube positioned towards the furnace wall (b), central radiant tube positioned towards the strip (c) according to [29].

It can be observed that maximum temperatures occur on the side of the radiant tubes facing the furnace wall ($\varphi = 0°$ to $\varphi = 180°$). The side facing the strip shows the lowest temperatures ($\varphi = 180°$ to $\varphi = 360°$). If the central tube is placed towards the furnace wall, the temperature of the tube on the upper side (maximum at $\varphi = 90°$) increases significantly. The minimum temperature at an angle of $\varphi = 270°$ remains unchanged in terms of location and quantity. The maximum temperature on the top side ($\varphi = 90°$) of the central tube drops approximately $\Delta T = 5\,\text{K}$ below the temperature of the right and left tubes with an offset towards the strip.

The heat flux on the strip is shown in Fig. 13. For a misalignment of the central tube close to the strip ($t_{\text{rt-wall}} = 1.5d$; $t_{\text{rt-strip}} = 0.5d$), a



(c)

Fig. 12. Circumferential temperature distribution on all three radiant tubes for different vertical distances between the radiant tubes and the furnace wall respectively the strip: all radiant tubes aligned (a), central radiant tube positioned towards the furnace wall (b), central radiant tube positioned towards the strip (c) according to [29].

maximum heat flux is observed directly below the middle of the central tube. With an offset towards the furnace wall ($t_{\text{rt-wall}} = 0.5d$; $t_{\text{rt-strip}} = 1.5d$), the maximum shifts to the space between the radiant tubes. The minimum is now located at the position of the central radiant tube. In contrast to the two distributions of the misaligned central tube, the heat flux distribution of the reference shows much more homogeneity. The difference between the maximum and minimum heat flux occurring on the strip section is the smallest with no misalignment and the highest with an offset towards the strip.

Positioning the central radiant tube close to the furnace wall leads to a significant increase in temperature on the wall directly above the tube, Fig. 14. The maximum wall temperature is $\Delta T = 33\,\text{K}$ above the maximum wall temperature for a central tube without offset. If the central tube is positioned close to the strip, the lowest temperatures can be observed compared to the other two setups. The opposite effect can be seen with the maximum temperatures of the wall directly above the right and left radiant tubes. Although the position of these tubes does not change, the wall temperature increases the closer the central tube is positioned to the strip.

It can be seen that an offset of the central tube towards the furnace wall or strip leads to higher variations in heat flux on the strip. An offset towards the furnace wall results in higher temperatures on the wall and on the radiant tube itself compared to an arrangement without any offset. The investigation shows that a misalignment of the radiant tubes does not seem to be beneficial at all.

3.4. Emissivity

The influence of emissivity was investigated with the help of three scenarios, Table 2. A variation of the emissivity is carried out for the tubes, furnace chamber, and wall sections in all zones. In each scenario, the emissivity for one of these three components is changed, while the emissivities of the other components are kept constant. It should be noted that the study covers a wide range of emissivities, which are not necessarily technically feasible. However, the results illustrate the sensitivity of the radiation exchange to a change in emissivity.

Table 2
Emissivities for radiant tube, furnace wall and strip for the three scenarios.

	Scenario 1	Scenario 2	Scenario 3
ε_{rt}	0.1; 0.3; 0.6; 0.9	0.9	0.9
$\varepsilon_{\text{strip}}$	0.6	0.1; 0.3; 0.6; 0.9	0.6
$\varepsilon_{\text{wall}}$	0.9	0.9	0.1; 0.3; 0.6; 0.9

The distance between the radiant tubes is kept constant at $t_{\text{rt-rt}} = 2.0d$ during the emissivity study. The distances from tube to wall and tube to strip are $t_{\text{rt-wall}} = 0.5d$ and $t_{\text{rt-strip}} = 0.5d$.

For the first scenario with variation in radiant tube emissivity, a change in the radiant tube temperatures can be observed, see Fig. 15. The highest radiant tube temperature occurs at an emissivity of $\varepsilon_{\text{rt}} = 0.1$. The highest emissivity included in the study, $\varepsilon_{\text{rt}} = 0.9$, leads to the lowest tube temperatures. At the same time, it is noticeable that the temperature gradient on the radiant tube increases with increasing emissivity. In scenario two, the emissivity of the strip was varied. An influence on the temperature distribution of the central radiant tube of the evaluated zone can be observed here, Fig. 16. A low emissivity of the strip leads to high temperatures on the radiant tube. In contrast to that, high strip emissivity leads to low tube temperatures. A change in the emissivity of the furnace wall in the third scenario does not lead to any change in the temperatures on the radiant tube.

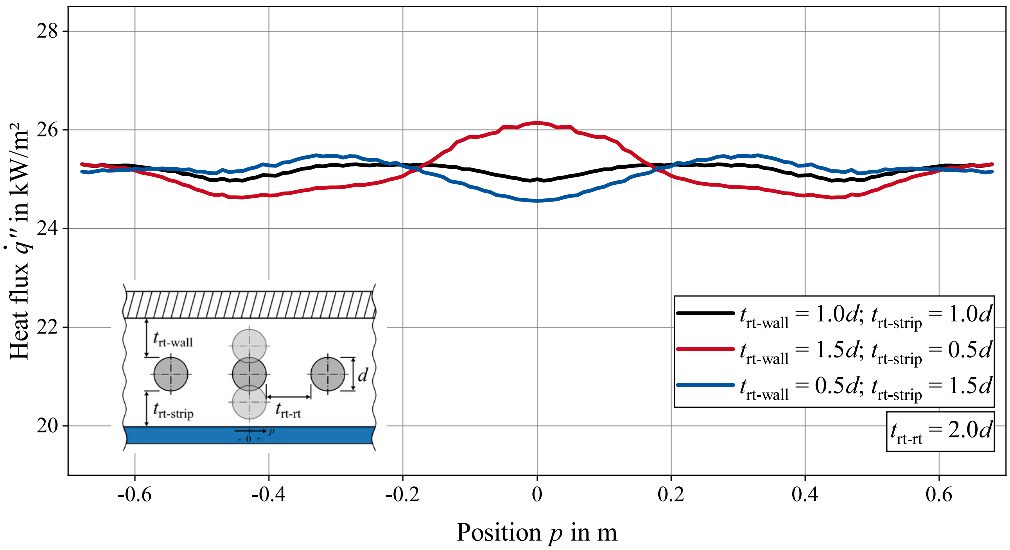


Fig. 13. Heat flux on the strip with a vertical misalignment of the central radiant tube according to [29].

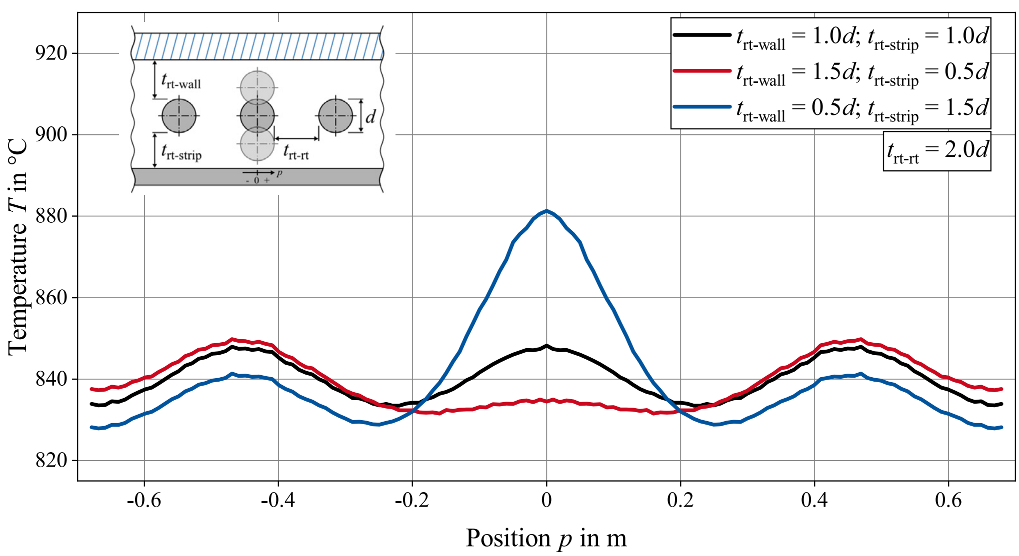


Fig. 14. Temperature distribution on the furnace wall with a vertical misalignment of the central radiant tube according to [29].

After the influence of the emissivity on the radiant tube temperatures has been analyzed, the focus is shifted to the temperature distribution of the furnace wall. A change in emissivity of the radiant tube (scenario one) does not influence the temperature distribution of the wall. However, for scenario two and the related change in strip emissivity, an effect on the temperature distribution of the furnace wall can be observed, Fig. 17. If the strip has a low emissivity, the highest wall temperatures occur. In contrast, the wall temperatures are lowest for the highest strip emissivity. The characteristic of the temperature maximum located directly above the center of the radiant tube also changes and is most pronounced when the emissivity of the strip is high.

If the emissivity of the furnace wall is changed as in scenario three, a change in the temperature distribution on the wall can be observed, Fig. 18. The temperature level changes, but the shape of the distribution on the wall remains the same. The lowest wall temperature occurs at the lowest emissivity of $\varepsilon_{\text{wall}} = 0.1$. From there, a change in emissivity to $\varepsilon_{\text{wall}} = 0.3$ means a jump in temperature of approximately $\Delta T = 20\,\text{K}$. A further increase in emissivity up to $\varepsilon_{\text{wall}} = 0.9$ leads to a temperature increase of approximately $\Delta T = 5\,\text{K}$.

The last parameter to be considered in the scenarios is the heat flux distribution on the strip. However, it is only influenced by a change in emissivity of the strip itself (scenario two). The emissivity of the radiant tube and also the emissivity of the furnace wall have no influence on the heat flux distribution. Fig. 19 shows the heat flux distribution on the strip at different emissivities. Minima of the heat flux distribution can be seen below each of the three radiant tubes. The maxima are in the gaps between the tubes. As the emissivity increases, the maximum heat flux also increases, and the minimum heat flux decreases. The smallest difference in heat flux between the maximum and minimum occurs at $\varepsilon_{\text{strip}} = 0.1$.

It should be noted that with the low emissivity of the strip of $\varepsilon_{\text{strip}} = 0.1$, the number of zones for the investigation was increased from 5 to 11. This reduces the stronger influence of the boundary conditions selected at both ends of the furnace due to reflection.

In general, it can be seen that the emissivity of the radiant tube, furnace wall, and strip cannot be neglected in a radiation analysis. For the lowest possible temperatures at the radiant tube, high emissivities of the tube itself and the strip are favorable. However, the emissivity of the strip cannot be influenced as it depends on the materials passing

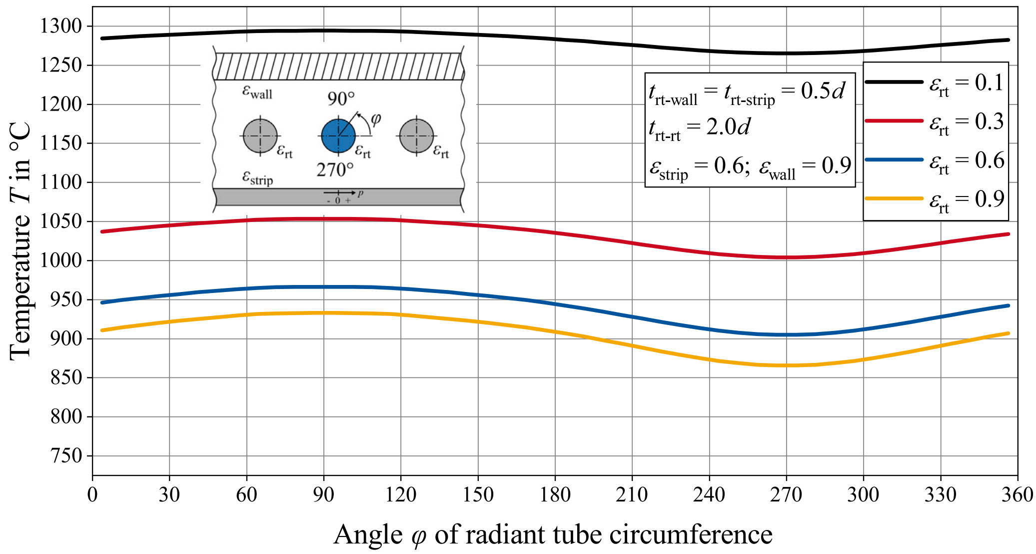


Fig. 15. Circumferential temperature distribution on the central radiant tube for different tube emissivities according to [29].

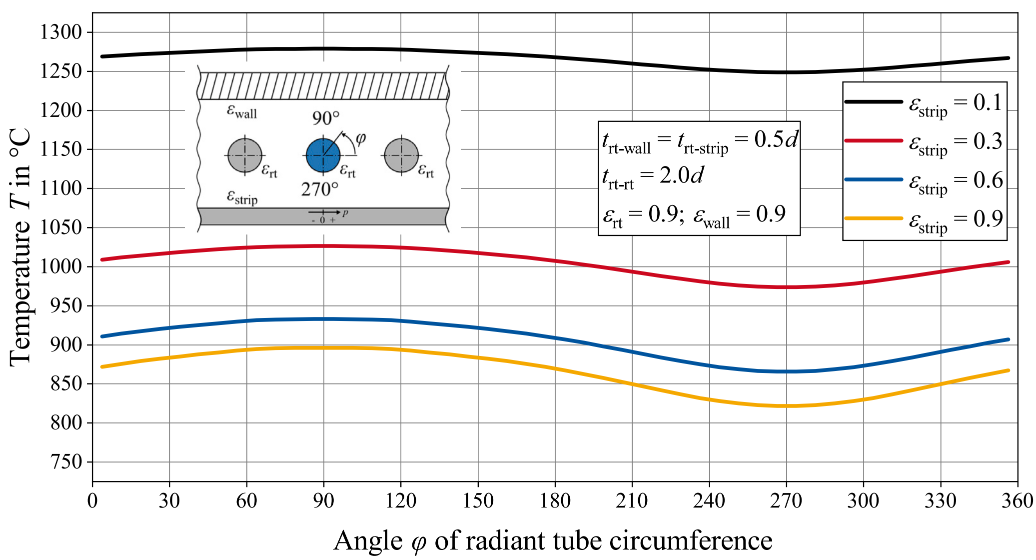


Fig. 16. Circumferential temperature distribution on the central radiant tube for different strip emissivities according to [29].

through the radiant tube furnace and their pretreatment. If the emissivity of the strip is low, increased radiant tube temperatures are to be expected. At the same time, the temperatures of the furnace wall also increase. The emissivity of the furnace wall has no influence on the temperature distribution of the radiant tube or the heat flux on the strip. However, the low emissivity on the furnace wall leads to lower temperatures on the wall itself.

4. Conclusion

Radiant tubes and their arrangement inside a horizontal radiant tube furnace were investigated. Radiation exchange within the furnace was calculated using a two-dimensional model based on the RadMod2D framework for radiation modeling. The aim here was to determine the effect on the temperature distributions on the tubes and furnace wall, as well as the heat flux on the strip. The results for the tubes must be taken into account in particular as they can be used as a basis for making assumptions about the radiant tube lifetime. The common installation recommendations have been checked, they apply, and now the data backing them is also available. This makes the problem comprehensible.

Different variations of the horizontal distances between the tubes and the vertical distance between the tubes and the furnace wall as well as the vertical distance between the tubes and the strip were investigated in order to find the ideal arrangement and therefore the optimal design of the furnace. An offset of the central tube was also considered as well as the influence of the emissivities of the components. A homogeneous temperature distribution at low temperatures on the tubes and the furnace wall, as well as a homogeneous heat flux distribution on the strip, are important evaluation factors. The investigations show:

- A horizontal distance of twice the radiant tube diameter between the tubes is optimal.
- For the vertical distance between the tubes and the wall and the tubes and the strip, both a distance half the tubes' diameter is optimal, with all tubes vertically aligned.
- The findings confirm common installation recommendations.
- A misalignment of the central tube, carried out with an offset in the direction of the furnace wall or the strip, has a negative effect on the uniformity of the heat flux on the strip.

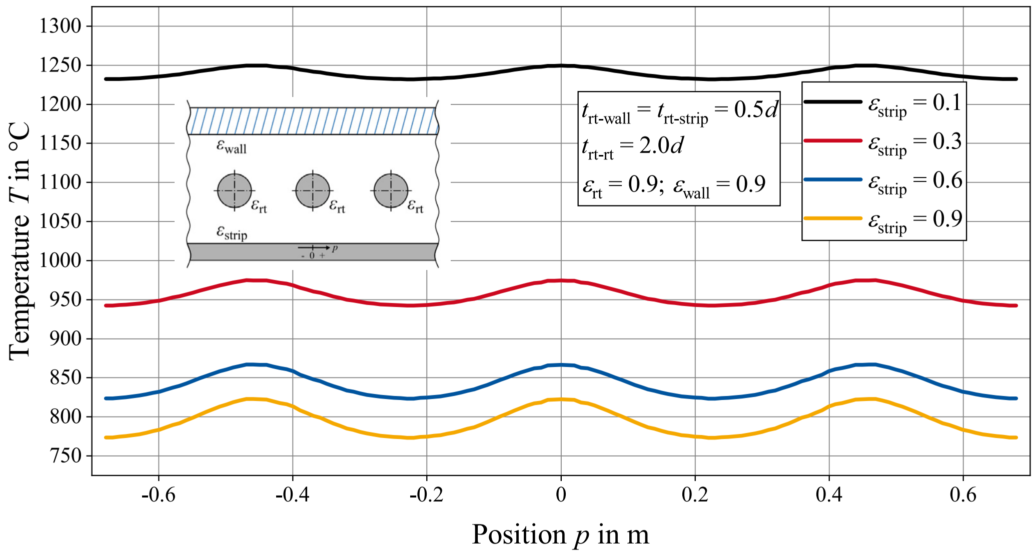


Fig. 17. Temperature distribution of the furnace wall for different strip emissivities according to [29].

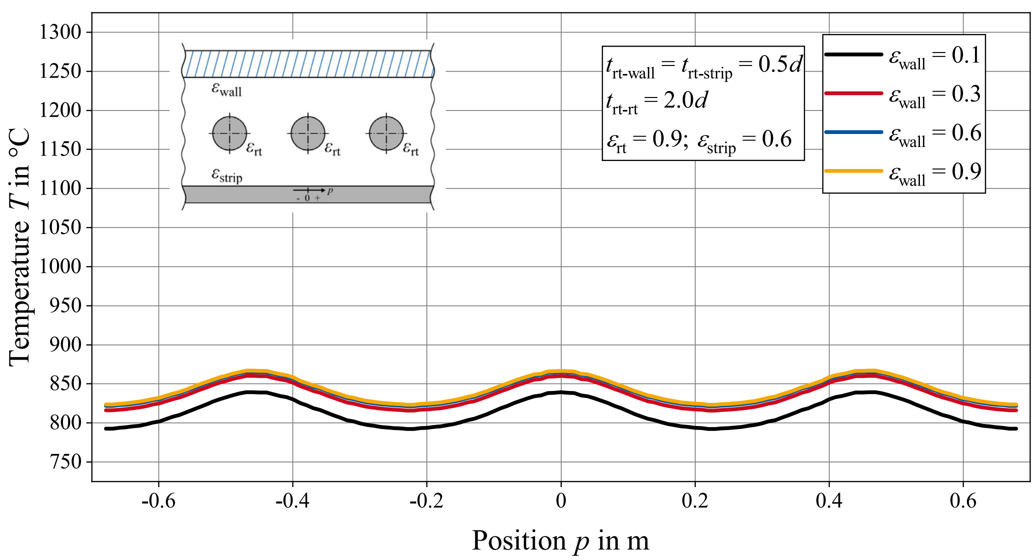


Fig. 18. Temperature distribution of the furnace wall for different wall emissivities according to [29].

- An offset of the central radiant tube towards the furnace wall results in higher temperatures on the wall and the tube compared to an arrangement without any offset.
- Radiant tubes with high emissivities lead to comparatively low temperatures on the tubes themselves.
- The strip's emissivity significantly influences the temperatures on the tubes and furnace wall, whereby high strip emissivity leads to higher temperatures on those components.
- The emissivity of the furnace wall only influences its own temperatures, but has no effect on the tubes' temperatures or the strip's heat flux.

The findings of the study can be applied to horizontal furnaces equipped with single-ended radiant tubes of continuous annealing lines for steel strips. Although the arrangement of the radiant tubes is a design decision of the furnace, in practice the emissivity can only be influenced to a very limited extent.

Further research will involve investigating radiation phenomena with a three-dimensional approach for the single-ended radiant tube as well as other tube types. Furthermore, the lower part of the horizontal furnace with its rollers has been neglected in the underlying investigations and should be considered. The presented method can be applied to the field of electric heating by means of heating elements, which is currently on the rise for decarbonization. The issues of element arrangement and lifetime are also of great interest here.

CRediT authorship contribution statement

Dominik Büschgens: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Herbert Pfeifer:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

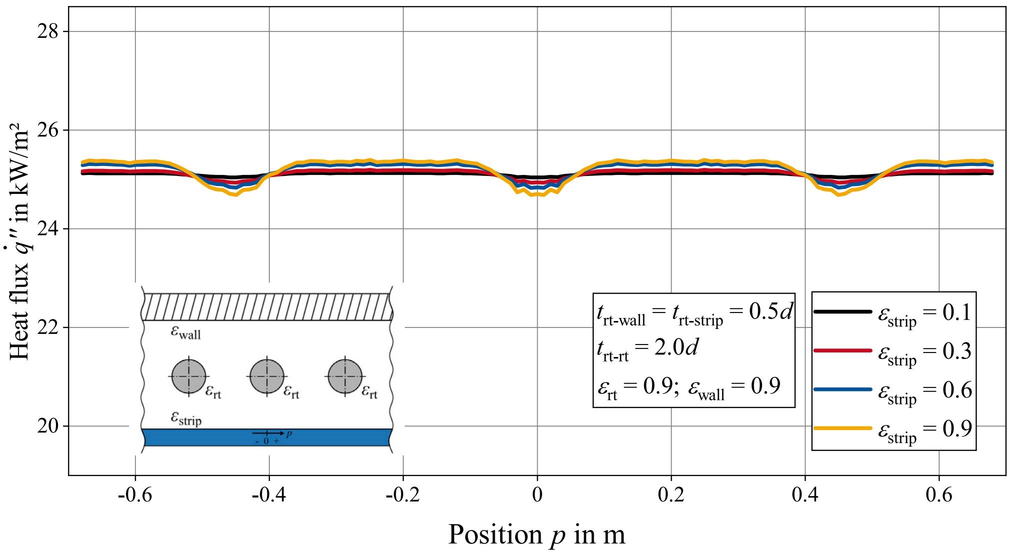


Fig. 19. Heat flux on the strip for different strip emissivities according to [29].

Data availability

Data will be made available on request.

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