Study on Thermal Comfort in Industrial Buildings, Heated by Radiation

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Abstract. This paper is focused on a study between different heating systems commonly used in industrial installations. Industrial heating systems generally raise difficult problems in choosing the most economical system. If several solutions technically meet the requirements of the indoor climate, in terms of energy efficiency we must focus on the optimal solution. The study was conducted to choose the optimal heating solution for an industrial hall, from the point of view of evaluating the efficiency of the installation of an exhaust gas recirculation equipment. The heating of industrial premises generally raises difficult problems due to the diversity of the types of buildings encountered, the variety of activities carried out and the need to choose the most economical system, both in terms of investment and operation. The radiation heating system using natural gas offers the solution of this problem, in situations where the classic heating systems (hot air heating or static bodies) cannot ensure optimal indoor conditions (in the sense that they do not achieve a relatively uniform temperature in the heated space, cause drafts and have low yields). For spaces with a high height (over 4m) these systems can only be considered satisfactory in the case of general heating with very high energy consumption. From the study performed, but also from the specialized technical literature, it is concluded that these systems offer an energy saving, compared to the classical systems.

1. Introduction
Reducing energy consumption and increasing the energy efficiency of buildings has attracted the interest of the scientific community, political organizations and industry worldwide. Thus, specialists in various fields, regarding the efficiency of the systems of installations for buildings, approach the energy efficiency in correlation with the assurance of the comfort in buildings with different destinations (residential, administrative and industrial) [1-9]. Due to the constructive structure type diversity and the performed activities variety, industrial buildings raise special problems regarding the indoor climate conditions specific to the industry. Heating industrial enclosures generally raise difficult issues in terms of choosing the most economical system, both in terms of investment in the heating system, but primarily of the operating process, since it generally involves large financial efforts [10].
An recent studies indicate that over 50% of global energy consumption is due to industrial sector [11]. But, in Romania, a certain inefficient energy utilization manner it is usually observed in all sectors of the economy, notably in the industrial sectors, which accounts for over 80% of energy consumption. Such high intensity is due to obsolete equipment’s and old technologies. Private enterprises as well as restructured and/or privatized state enterprises are actively exploring cost reduction and efficiency improvement strategies because of the rising prices of the energy (gas, electricity and district heating) and aiming to improve competitiveness through energy efficient technologies [12-16]. Figure 1 shows that in Romania, the industrial sector has reduced its share of total energy consumption, reported to 2000 year [17].

![Figure 1. Final energy consumption by sector [17].](image)

However, actual investments in energy efficiency are low. This is, generally due to the absence of appropriate funding mechanisms, coupled with a lack of expertise in identifying and developing commercially viable projects. A case study was considered for an industrial building, with relatively large plan dimensions, having a ground surface of 3500 m² as typical for industrial constructions. This case shows the advantages of a radiation heating system compared to other conventional systems. The advantages are growing as the volume of the building is higher or when using gas-fired radiant tubes with recirculation.

2. Materials and Methods
Calculation of design heat demand was developed in two possible solutions: heating with hot air system version and heating by radiation system as alternative.

2.1. Types of systems analysed.
There were proposed several possible scenarios for industrial space heating systems: system using classical radiant tubes, system using radiant tubes with recirculation and system using fan heaters supplied with thermal agent supplied by a boiler.

The equipment and appliances analysed comply with the technical conditions and requirements imposed on heating appliances powered by solid, liquid or gaseous fuels, regulated by available rules [18], as well as the requirements regarding the marketing of products [19]. Typical activity in industry requires specific climate conditions for the technological process development (to ensure and guarantee the products quality) and on the other hand a suitable climate to workers activity, in order to achieve a higher work productivity. Thermal comfort conditions for occupants of buildings are regulated by international/national standards such as ISO or ASHRAE [9], [20-21]. Most often, technological processes demand corresponds to indoor climate conditions appropriate as well to human labour, due to tolerances existing in every situation. When these requirements cannot agree simultaneously, technological necessities prevail for workers and thus it is going to intervene through additional installations or equipment suited to the conditions imposed by the production process. Considering that the working efficiency largely depends on the microclimate conditions, the priority is
aimed to ensure first the conditions of work and consequently to design the most appropriate heating installations in order to ensure high productivity. The total indoor conditions, contributing of an appropriate ambient ensuring the people feel comfortable and in the same time to operate with high productivity, define the so-called comfort. The perception of comfort is ensured by several mainly factors related to normal heat exchange between man and the environment, and which constitutes thermal comfort, but also by a number of secondary factors. It can also be said that in sensorial terms thermal comfort means the lack of unpleasant heat or cold sensation.

In industry it is not usually to speak about thermal comfort but of working conditions, corresponding to a particular activity. So, when references are made to working conditions, there are taken into account internal parameters values that on the one hand provide high productivity of the labour development and on the other hand ensure people’s health. Indoor air temperature is one of the major factors on thermal comfort and we can action influencing on it directly by using a heating or ventilation plant. At relatively low variations of indoor air temperature the regulator quickly comes into operation and restores the heat exchange between human and environment. The air temperature must be higher in rooms where people rest or perform easy workplace, and lower as the activity requires a more significant work. Thus, for this specific case, the workspace will be considered as having normal releases of heat and humidity, as the work accomplished fits in the average work category.

One hand, the indoor air movement speed must “match” to the air temperature and on the other hand must be corresponding of the occupier’s type of activity. In industrial spaces it is bothering when the air is moving with a lower temperature than the indoor room temperature during winter season, mostly if the jet is directed toward specific body parts. On the contrary, in summer, the air moving with greater speed creates a pleasant feeling of cooling even if the air’s temperature is identical to the ambience one. Sensitivity to air movement feeling is very different in humans and dependent on health status, sex, age, clothe, season etc. accordingly to demanded comfort, conducting also to different limits for air movement speed. To a very high degree of thermal comfort in cold season, a speed between 0.12-0.15 m/s limits correspond to the air movement, while for a production enclosure, with intense activities, a 0.50-0.60 m/s speed of the air movement is appropriate. In the warm period of the year the air movement speed has significantly higher values. Average radiation temperature determines the scale of radiant heat exchange between human and environment. The average radiation temperature should always be correlated with indoor air temperature. Increasing the average radiation temperature must be accompanied by indoor air temperature lowering and vice versa.

Indoor air temperature and average radiation temperature play a decisive role on thermal comfort. The human body always apprehends the simultaneously combined effect of these temperatures, this being the reason for introducing the notion of resultant of “perceived temperature”. Resultant temperature, \( t_r \) usually is calculated as the arithmetic mean between indoor air temperature and average radiation temperature. Resultant temperature is indirectly influenced by the used heating system. For the adopted heating system, it results a specific average radiation temperature (for a certain building) and therefore a specific radiant exchange of human with delimiting surfaces which leads to a certain temperature perceived by occupants. It follows that for the same room, equipped with various heating systems, the resultant temperature will be different, so it should practically be another resultant temperature for each case. Arithmetic mediation does not correspond entirely on physical reality. As an example, for the resultant temperature \( t_r \) in rooms equipped with radiation heating systems it should be used this type of relationship (1), where, \( t_i \) is indoor air temperature and \( t_{ms} \) is the average radiation temperature:

\[
t_r = 0.45t_i + 0.55t_{ms}
\]
Considering all this, it could be drawn a first conclusion, that the radiation heating system allows maintaining the indoor air temperature at levels two to four (2 to 4 °C) degrees lower than a traditional heating system. This is possible because using a radiation heating system increases the average radiation temperature of surfaces in the incidence cone of radiation and thus maintaining the same resultant temperature requires a lower indoor air temperature.

It follows therefore a smaller heat requirement when using radiation heating system toward a hot air heating system that will be as lower as the air volume of the building is higher. This is one of the final conclusions of the feasibility study, demonstrated by calculations.

2.2. Technical and economic considerations

Only the justification from thermal point of view for a heating system in industrial building is not enough to decide when a relatively large investment as one involved in the industrial sector. Displayed solutions equivalent in their energy effect can be compared based on the following criteria:

- Criteria for calculating costs – represents the establishment of a synthetic indicator, also of an annual expenditure calculation covering annual costs of the solution and the product of the normal coefficient of economic efficiency and investment value.

- Criteria for updated total costs - is normal criteria including all expenditure (investment, production and other expenses) during the study, reported by technical update at some point for a comparison solutions.

- Payback criteria - is the criteria that determines the duration of the recovering the extra investment and spending in a solution versus another they compare.

Economic criteria underpinning choosing an industrial heating system are related to equipment acquisition costs, installing labour costs and operating expenses that involve the fuel and electricity consumption in order to achieve proposed thermal conditions, as well as maintenance personnel and repairs. The largest share in the operating expenses is the fuel cost. Given the close values of thermal efficiencies for production, transport, regulation and heat distribution in the warmed room, solutions’ differentiation is through the electricity consumption its cost. Most often, the solutions leading to the lowest investment cost do not have the lowest operating costs, the best solution being the one that leads to minimal computing costs.

3. Results and discussions

3.1. The simulating the dynamic regime using TRNSYS

We consider interesting the presentation of the results by simulating the dynamic regime using the soft simulation program TRNSYS for the considered building with various height schemes. Data on the heat requirement calculated with TRNSYS program for classic and radiation heating are in the table 1:

| Height of the enclosure [m] | Qc [kW] | Qr [kW] |
|----------------------------|---------|---------|
| 12m                        | 540,08  | 408,7   |
| 10m                        | 485,5   | 360,33  |
| 8m                         | 434,7   | 321,2   |
| 6m                         | 389,2   | 280,5   |

Qc - is heat demand for classic heating; Qr - is heat demand for heating radiation.
The variation of the thermal load by the temperature for a deposit and for different heights (6 m and 12 m) are simulated for the two analysed systems (Figure 2 and Figure 3). The simulations were performed for December. The figure 4 comparatively shows the variation of annual gas consumption, depending on the type of heating system and the height of the warehouse.

**Figure 2.** Thermal load variation by the temperature for a warehouse with a height of 6 m

**Figure 3.** Thermal load variation by the temperature for a warehouse with a height of 12 m

**Figure 4.** Variation of annual gas consumption depending on the heating system and enclosure height
3.2. Gas-fired radiant tubes with recirculation

For radiant tubes with recirculation, a specific study was conducted, starting from design to experimental implementation of a recirculation device on a regular radiant tube. Reintroduction of exhaust gases must be effectuated between the burner and the first part of the radiant tube. The optimal position for the recirculation part is considered as adjacent element to the radiant tube. This is the easiest way considered, as no changes are made to the radiant tube in the series production, thereby achieving minimal costs for modular recirculating radiant tube. The working principle consists in reintroducing a part of the flue gas volume which would be discharged back into the radiant tube circuit (Figure 5).

![Figure 5. The recirculation part made in the Faculty of Building Services Engineering Laboratory](image)

Although the basic idea is the recovery of an amount of heat, in reality, the exhaust gases recirculated are used to create a superficial layer of flue gas cooler towards the flame, aiming to prevent rapid release of heat in the first section of tube (basically it slows the transfer of heat by radiation and convection between the heat and the fumes and the tube wall in the area where the flame is present). This amount of heat is actually recovered in the first section of the tube and swing in the second part thereof, thus obtaining better temperature uniformity over the entire length of the tube radiant.

The functioning of a system with recirculation is to allow a quantity of exhaust gas to be sucked back into recirculation element. This is possible because the evacuation of exhaust gases have positive pressure and the outlet engage into the recirculation element is characterized by a negative pressure, which results in exhaust fan generated vacuum. Quantitative adjustment of the recirculated exhaust gases is achieved through a clogged dampers allowing total stop in the recirculation route. With the gradual opening of this damper, it can be reached an exhaust gases recirculation up to a rate of approx. 86%.

3.3. Experimental study for recirculation radiant tubes parameters

Measurements were carried out on a standard tube (with a length of 6m) to which was fitted the recirculation piece according to the project and also on the elongated tube of 8 m equipped with the recirculation track. It should be mentioned at the beginning that the measured gas pressure at the outlet of the electro-valve is not proportional to the amount of consumed fuel only for the same recirculation piece. Measurements were conducted with gas pressure of 6.9 mbar (identical to the one given by manufacturers) to obtain a thermal load of 24 kW indicated by the manufacturer. The purpose of these measurements was to experimentally verify the technical features offered by the manufacturer. The results confirm that indeed, by regulating the burner gas pressure value to 6.9 mbar, a 2.96 Nm³ hourly consumption is obtained. The heat flow emitted through radiation was calculated based on the radiant tube’s average temperature purchased by an acquisition Almemo station from surface temperature probes mounted at equal distances and it was used as a comparative benchmark for the rest of the measurements.
Comparison analysis highlights an efficiency combustion increase by 3% compared to the standard radiant tube and radiant heat flow of 1.2 kW. Simultaneously with the measurements session there were performed simulations of radiant tube with a program developed in C++ realized in order to simulate the temperatures on the surface of a recirculating radiant tube. By using it they could perform simulations for estimating the data there is to be obtained. In the most general form of the equations that describe the heat transfer processes characteristic to the radiant tube are [12-13]:

- The equation of convective and radiative global heat transfer (equation 2) between the exhaust gases and the inner surface of the wall:
  \[ Q_1 = \alpha_g \cdot (T_{gi} - T_p) \cdot A_{pi} \] (2)

- The equation of convective and radiative global heat transfer (equation 3) between the outer surface of the tube and the ambient (indoor):
  \[ Q_2 = \alpha_c \cdot (T_p - T_0) \cdot A_{pe} + C_0 \cdot 10^{-8} \cdot \varepsilon_p \cdot (T_{pe} - T_{04}) \cdot A_{pe} \] (3)

- The equation of conduction heat transfer equation in the radiant tube’s wall (equation 4):
  \[ Q_3 = \frac{(T_{pe} - T_p)}{\ln \frac{d_e}{d_i}} \] (4)

- The equation of calorimetric balance for exhaust gases (equation 5):
  \[ Q = D_g \cdot c_{pg} \cdot (T_{gi} - T_{ge}) \] (5)

- The equation defining the initial condition \( T_{gi1} = TT \) - theoretical combustion temperature:
  \[ TT = \frac{H_i + \alpha V_0 \cdot c_{pg} \cdot c_{ao}}{[V_{go} + (\alpha - 1)V_0] \cdot c_{pg}} \] (4)

where:
- \( A_p \) [m\(^2\)] - the radiant tube surface;
- \( T_p \) [K] - radiant tube wall temperature;
- \( T_{gi}, T_{ge} \) [K] - exhaust gases temperature at inlet and outlet of the elementary considered area;
- \( \alpha_g \) [W/m\(^2\)K] - convective and radiation global heat transfer coefficient from the flue gases to the tube wall;
- \( \alpha_c \) [W/m\(^2\)K] - convective heat transfer coefficient from the outer surface of the tube to the ambient air;
- \( \lambda \) [W/m K] - conduction heat transfer coefficient in the radiant tube wall;
- \( \varepsilon_p \) [-] - emissivity coefficient of the radiant tube;
- \( C_0 \) [W/m\(^2\)K\(^4\)] - absolute black body radiation coefficient (5.67 W/m\(^2\)K\(^4\));
- \( \alpha \) [-] - air excess of the burner fuel combustion;
- \( D_t \) [Nm\(^3\)/h] - the normal flow;
- \( c_{pg} \) [J/Nm\(^3\)K\(^4\)] - average specific heat of exhaust gas;
- \( H_i \) [kW/Nm\(^3\)] - inferior calorific heat of fuel, in kW/Nm3;
- \( T_0 \) [K] - ambient temperature;

Indices: p - wall; g - gas; i – index referring to “indoor or inlet”; e - index referring to “outdoor or outlet”.

The tube wall surface is divided and also the radiating gas volume in elementary areas (ranges) defined by elementary length dl. After defining the radiant tube geometry and the constant values that
To recirculate the total amount of produced gas, the gas flow in the tube is formed by summing up the flow produced by burning the fuel $D_{t+273}/273$ and produced gas flow $D_N$. After reaching the speed limit, it is reached the recirculation functioning mode characterized by a flue gas flow consisting in: 80% of the exhaust gas from the previous circulation $0.8 \cdot D_g$ and 20% from fuel combustion $0.2 \cdot D_{t+273}/273$, the savings are to use only 20% of the initial amount of fuel. The calculation continues until the flowing through the tube is stabilized: the flow rates are compared from the last 10 circulations. When these speeds (real numbers) are equal it is considered a stable flow regime.

Materialized attempts by attempts bulletin BI16 or BI19 could be predicted by the calculation program. This computer program will be used further in the attempt to improve the recirculating system and to adapt the recirculation radiant tube recirculation piece with flue gas vacuum circuit of higher power and longer lengths. All the data from experiments were summarized in the table 2.

**Table 2. Centralization of obtained experimental data.**

| Test number bulletin | The type of the equipment | With/without recirculation | The length of the radiant tube [m] | The gas pressure [mbar] | Fuel consumption [Nm³/h] | Measured efficiency [%] | Emitted flux by radiation [W] |
|----------------------|--------------------------|---------------------------|-----------------------------------|------------------------|-------------------------|-------------------------|-----------------------------|
| BI01                 | Standard equipment       | Standard                  | 6                                 | 6.9                    | 2.96                    | 85.6                    | 13632.87                    |
| BI09                 | Standard                 | Standard                  | 6                                 | 3.5                    | 2.34                    | 84.6                    | 10651.28                    |
| BI10                 | Recirculation            | Standard                  | 6                                 | 3.5                    | 2.14                    | 87.8                    | 12306.51                    |
| BI11                 | Standard                 | Recirculation             | 6                                 | 4.5                    | 2.61                    | 86.4                    | 11912.82                    |
| BI12                 | Recirculation            | Standard                  | 6                                 | 4.5                    | 2.43                    | 86.8                    | 12608.69                    |
| BI13                 | Standard                 | Recirculation             | 6                                 | 5                      | 2.64                    | 86.1                    | 12582.77                    |
| BI14                 | Recirculation            | Standard                  | 6                                 | 5                      | 2.51                    | 87.8                    | 13841.97                    |
| BI15                 | Recirculation            | Standard                  | 6                                 | 6.9                    | 2.95                    | 88.4                    | 14995.86                    |
| BI16                 | Recirculation            | Standard                  | 6                                 | 9                      | 3.31                    | 88.4                    | 17864.82                    |
| BI17                 | System with recirculation | Standard                  | 8                                 | 6.9                    | 3.07                    | 89.9                    | 16104.73                    |
| BI18                 | Recirculation            | Recirculation             | 8                                 | 6.9                    | 2.8                     | 91                      | 16143.05                    |
| BI19                 | Recirculation            | Recirculation             | 8                                 | 6.9                    | 3.07                    | 90.6                    | 16458.62                    |
| BI20                 | Recirculation            | Recirculation             | 8                                 | 8.6                    | 3.19                    | 91.8                    | 17407.18                    |

**4. Conclusions**

Conclusions from the measurements and analysis of and the test reports are:

1. An improvement of the temperature uniformity on the radiant tube surface it was obtained, for the case of the 6m length radiant tube usage, with a recirculation system.
2. The average temperature on the tube’s surface and radiative transmitted heat flow between the tube and the floor has increased in a range between 6% and 18%.

3. The differences between the recorded temperature values on the tube’s surface shrinks, the temperatures on the ongoing circuit are lower compared to a standard tube (without recirculation), but the temperatures on the return circuit are higher.

4. Given the same heat flux emitted into the room, between the fuel consumption of INFRA 6B and the standard radiant tube is a difference of approx. 15% for recirculation.

5. There has been an increase in combustion efficiency from approx. 86% on the radiant tube without recirculation to approx. 92% on the recirculating radiant tube, given the conditions of performing pollutants measurements at a combustion air temperature of approx. 36 °C [22]. In terms of performing tests in the cold weather (air temperature of max. 15 °C) we estimate that these values can reach approx. 93% - 95% for the recirculating radiant tube;

6. By transforming the radiant tube having length of 12m (U section of 6m) in a tube having 16m (8m length U section), radiated flow into the room increases by 18% without increasing the fuel consumption;

7. Recirculation system was designed as an optional element, which can be easily mounted on standard radiant tube through a cone sealing and screws devices;

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