JOURNAL OF ENERGY SYSTEMS

2023, 7(3)

2602-2052

DOI: 10.30521/jes.1198583

Research Article

Development and evaluation of an energy-efficient intelligent infrared heating system for industrial buildings

Denis Chikurtev
Bulgarian Academy of Sciences, Institute of Information and Communication Technologies, Sofia, Bulgaria, dchikurtev@gmail.com
Veneta Yosifova*
Bulgarian Academy of Sciences, Institute of Information and Communication Technologies, Sofia, Bulgaria, veneta.christova@gmail.com
Milena Haralampieva
Bulgarian Academy of Sciences, Institute of Information and Communication Technologies, Sofia, Bulgaria, milena_biserova@abv.bg
Rosen Petrov
Bulgarian Academy of Sciences, Institute of Information and Communication Technologies, Sofia, Bulgaria, rosen_p@yahoo.com

Submitted: 03.11.2022
Accepted: 27.07.2023
Published: 30.09.2023

* *Corresponding Author*

Abstract: Energy efficiency is a global problem that has become a top priority for all developed countries in recent years. Limited energy resources and high pollution worldwide have led to an increase in research and development in terms of energy efficiency. In the present work, one of the energy-efficient methods for heating by using infrared sources is focused. The advantages of infrared heaters compared to standard heating sources are underlined. A comparative study of the energy consumed during heating by the most frequently used by the heating systems has been made, and the results of the theoretically calculated power costs are presented. An intelligent system has been developed for the management of the infrared heaters to reduce the consumption of electricity better. The intelligent control system is based on a fuzzy-logic control and an internet of things. Results of simulation experiments of the intelligent system are presented as well as of the application of the system in a real environment. During the experiments, the system successes to control the heaters and to reduce power consumption. The achieved results prove that signal processing and control can improve the performance by using modern sensor systems, thereby additional efficiency can be achieved by using the infrared heating. It is possible to develop different optimization systems and algorithms for increasing the energy efficiency of different heating systems.

Keywords: *Energy efficiency, Fuzzy-logic control, Infrared heating, Intelligent control, IoT*

Cite this paper as: Chikurtev, D., Yosifova, V., Haralampieva, M., & Petrov, R. Development and evaluation of an energy-efficient intelligent infrared heating system for industrial buildings. *Journal of Energy Systems 2023*; *7*(3): 277-289, DOI: 10.30521/jes.1198583

Nomenclature	
EU	European Union
IoT	Internet of Things
HVAC	Heating, Ventilation and Air Conditioning

1. INTRODUCTION

In the modern world, energy efficiency and energy saving are some of the most popular topics needing further exploration. Today's energy demand is as high as ever, energy sources are limited, and the need for more efficient consumption increases. With the rise of energy prices, so rises the need for a variety of cost-effective and energy-saving solutions for heating in the cold season, especially for large spaces such as industrial buildings [1].

According to EU Energy Efficiency Directive and the European Green Deal, many buildings should be renovated in terms of energy efficiency - a benchmark of 49% of renewables in buildings is set by the year 2030 [2].

In the 1990s started the application of intelligent methods to the control systems of buildings. This is how Artificial Intelligence takes place in all kinds of buildings and algorithms are developed for adapting to the building's needs. In addition, the automation systems such as thermostats are inserted to guarantee interaction between the system and the users. This way all preferences of the inhabitants can be obtained [3].

Architects, engineers, and designers of HVAC systems face many challenges when it comes to designing systems for heating large industrial spaces. Recently many industries are facing difficulties in keeping up with the energy demand for their production needs. This is why decreasing the energy for heating will be a relief. As part of the research on effective heating methods in industrial buildings, a series of observations with thermal camera was made over industrial premises. The goal was to better understand the problems that may occur in terms of energy efficiency. The experiments were held during the winter season of 2019/2020 when the temperature difference can be spotted more clearly. Based on that research the following conclusions were made:

- *It is necessary for the production buildings to have high ceilings. Since most heating and ventilation systems work on the convection principles, the hot air goes up to the ceiling and the workstations remain cold.*
- *Most old production buildings have inefficient old construction elements such as steel-framed, uninsulated walls, old heavy doors, etc. This way, because of the temperature difference thermal bridges appear. This makes the popular heating methodologies not so efficient, which rises the heating costs.*
- *Because of the production technologies, not the whole space of the building needs to be heated, but only the workstations. In these cases, infrared heating can be useful, especially combined with smart control.*
- *Many entrepreneurs and building owners face more challenges in heating but are open to putting more effort into improving energy management with new intelligent technologies. This way, the heating process can be tailored according to working habits and production peculiarities [4].*

Many situations in large spaces, such as semi-open structures, storage buildings, manufacturing halls, etc., can be optimized with infrared heating. It has many advantages like lack of heat loss, easy maintenance, safe work, bespoke installation. For increasing the energy efficiency, improving the temperature comfort, and reducing the heating costs it can be combined with management systems and internet of things (IoT) [5,6].

Some advantages of this type of heating over conventional heating technologies are as follows: Radiant heat presents an exchange between the source and the object, and it doesn't heat the surrounding air, which leads to energy reduction and cost savings. The process does not need any preheating. This increases the heating cycle and makes it suitable for cost-effectively heating at frequently used large spaces. Radiant heating systems work on the same principle and have the same properties as light, so the heat can be reflected and focused, this means that the heated objects can start to reflect heat once they are heated [7].

These and many other advantages make infrared heaters efficient by using less energy of unit heaters for heating in large commercial and industrial buildings [8].

In the literature, the works combining energy efficiency, information and communication technologies are constantly evolving for two decades. Many new approaches for system analysis and control are developed. More popular are data-based system analysis, data information processing, and control by using analysis and control methods with data from meter sensors. To achieve better energy efficiency and create green buildings, the demand for multifunctional building management systems is increasing. Modern integrated building systems and intelligent control use a huge amount of data for machine-learning management and deep data based-analysis and control methods. Modern control systems combine many technologies such as communication systems, the Internet of things, and Smart automation [9]. By using them, a well-developed intelligent infrared system can be tailored for the requirements of building and specific processes inside for achieving better energy results [10]. The advanced control systems can be combined with computational intelligence and fuzzy logic. Technologies such as computational intelligence have many applications in different industries not only for heating but for a variety of processes. In this way, a multi-agent control system, which can solve complex problems for heat preservation and comfort can be designed and implemented [11].

The present work presents a model of an intelligent infrared heating system for increasing energy efficiency in industrial buildings. It is designed to be flexible and can read and analyze data from sensors. The system efficiency is compared to popular heating methods for industrial buildings. The experimental work confirmed the system's energy efficiency in terms of energy consumption. It is believed that the research contributes to the development of power systems by using modern control methods and innovative technologies based on the IoT, cyber-physical systems and smart devices. In the field of energy efficiency, the study shows how to significantly optimize some processes and apply technologies from other areas. The studies presented and the results obtained can be used to manage different heat sources as well as different systems. Analogical systems can be applied not only in industrial buildings but also in every building with wide spaces such as concert halls, sports infrastructure, etc.

The article is organized into the following chapters. In the second chapter, the developed intelligent control system for infrared heaters is presented. Chapter 3 presents a comparative analysis of infrared heating compared to other types of heating when applied in industrial premises. In the next chapter, the algorithm for optimizing the infrared heating system is presented. Chapter 5 includes the experiments done and the results obtained. Finally, a conclusion is presented regarding the achieved results and planned future research.

2. DESCRIPTION OF THE DEVELOPED AND PROPOSED HEATING SYSTEM

Based on the research of modern methods for intelligent management of infrared heating for industrial premises we propose a model of two infrared heaters with integrated intelligent control units in order to discover such system advantages in terms of energy efficiency (Figure 1). The methodology of building and operating is based on reading and analyzing wireless sensor networks information, fuzzy logic, machine learning, and IoT [12]. The model is a system made up of heating devices, sensors, and control devices. This system is based on modern smart home technologies and uses image processing [13]. The system's function is to ensure optimal use of heating appliances in an industrial room, achieve a comfortable environment for workers, and minimize energy consumption.

The main components of the system in Fig. 1 are as follows: 1) infrared heaters; 2) temperature sensors; 3) motion sensors; 4) computer; 5) Wi-Fi modem; 6) thermal camera; 7) embedded controllers.

The development of the system is based on web technologies also, in terms of the communication systems, LoRa technology is used. It allows a large number of devices to be connected to one for collecting data. The use of this technology enables the intelligent system to be expanded and applied to multiple rooms in one building. The management of each room can be monitored and managed both locally and globally through a specially developed user web graphical interface.

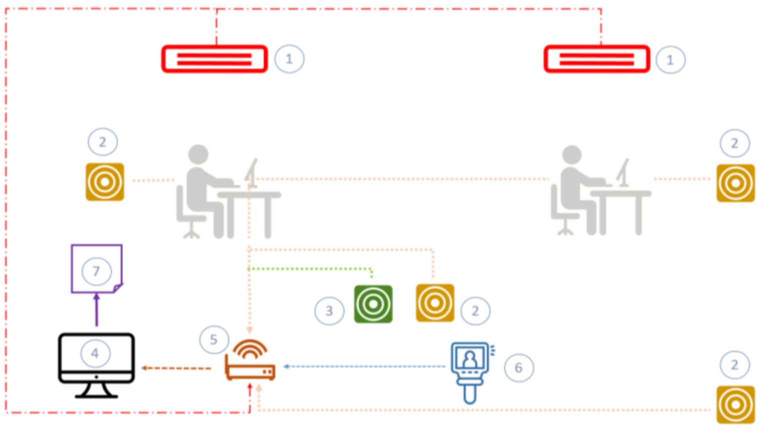

Figure 1. The design of an intelligent infrared heating system.

For maintaining the desired temperature, the system completely independently controls the operation of infrared heaters in autonomous mode. The algorithm is divided into two main cycles. The first cycle is switching the system on and off, the second cycle regulates the power of heating. The heating is switched on when the motion sensor detects movement and the camera identifies that there are people in the heated working area. Then, based on several factors such as the air temperature, the humidity of the air, the temperature of the common surface, the number of people, and the desired temperature, the system regulates the required powers on the infrared heaters. Each heater is powered on/off by a relay. Thus, every heater could be considered a smart device. The measurements are put together in one block, including the data from the thermal camera. The power of the infrared heaters is regulated in real-time, according to the changes in the indicators. We assume that the area of the heated area is constant and is pre-set [10].

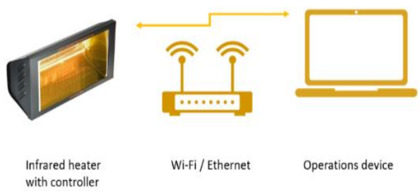

Figure 2. The communication principle of the system.

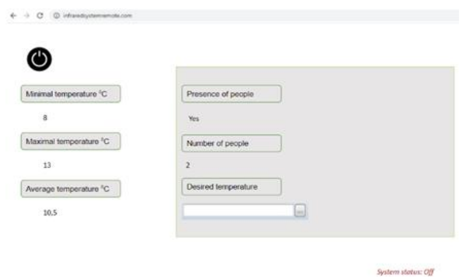

Figure 3. The interface of the designed system

The proposed system is combining the operator's computer with a controller connected via a Wi-Fi router to the infrared heater (Fig. 2). An internet connection provides the opportunity for remote control from different locations for maximum functionality. The whole controlling panel merges different technologies like the Internet, LoRaWAN for communication and control of IoT devices. This way, the system can complete different actions, based on an algorithm combining readings from thermal cameras, sensors, and infrared heaters. This algorithm is written in 'JavaScript' as a part of the applications. The system allows the operator to use it manually from a user-friendly interface (Fig. 3). Such a system can be developed and expanded with more devices and LoRa gateways, so that we will be able to control more appliances in different rooms, for increasing the energy efficiency of the whole space [9]. Data readings are processed clearly so that no information is lost during the readings [14].

3. INFRARED HEATING SYSTEM COMPARED TO OTHER HEATING SOURCES

The experiments are conducted during the winter season (i.e. 2021 and 2022) when the most energy is used for heating. The experiments are conducted in a large unheated industrial space with the following dimensions: width 6.5 m, length 12 m, and height 3.5 m. One of the long sides is fully glazed with Aluminum window profiles.

To prove the efficiency of the zonal heating, a working area of the room with approximate dimensions of 2 by 4 m is observed. The main characteristics of the building's features due to structure are described in Table 1. Two VARMA WR65 / 20 infrared heaters with a power of 2000 W each are connected to the system. They can be used for indoor and outdoor structures and each body can heat up a surface around 15 m by 20 m. The biggest advantage is that they do not need to work thru the whole day to keep the inside temperature constant. Infrared heaters warm the surfaces and the people in workspaces, they do not warm the air. They cannot be used to maintain a constant temperature in a room, but they warm people when they are in the heating/radiation area. They can be switched only when the workers are at their station. They can work together or separately, depending on the work demands of full or half power [15]. Another advantage of this type of heater is the instant warming effect. It only takes a few seconds from turning on the heaters for the people to feel warm. Therefore, the switch-on time is immediate when there are people in the workplace.

Another important parameter related to the specific properties of infrared heaters is the required distance between the emitter and the person. According to the power of the heater and its specifics, the recommendations from the manufacturers must be followed and their installation must be at an optimal distance from people so that an appropriate heating temperature can be achieved not to cause overheating. For example, with the used model of heaters, the recommended distance between a person and the emitter is 1.5 meters. At this distance, the person will feel a warming effect with a temperature of about 23°C – 24°C, which is a recommended working temperature according to most standards. But at different room temperatures, this sensation will change. Therefore, we need to be able to control the power of the heater in degrees. Thus, at an indoor temperature close to normal, the heater can operate at half power, and at a very low indoor temperature at maximum power.

The presented advantages of infrared heating sources allow to build a heating system with a separate working principle, different from standard heating methods. Here, the operating time of the heaters should be reduced as much as possible - only when there are people at work. This is why, the main element of the operation of the system will be the control of the devices depending on the presence of people. It will be read by a thermal camera that detects the presence of people according to their body temperature [16]. In addition, environmental temperature parameters and other factors must be taken into consideration. Under various factors, an algorithm for system operation is built.

One of those factors is heat lost. It is characterized by the transfer of heat through the surrounding construction of a building from inside to the outside that can occur from conduction, convection or radiation [17]. Heat loss is an important issue for reducing energy consumption and increasing energy efficiency in any type of building. Most of the energy loss is going through the surrounding construction elements. For example, 35% of the heat goes out through the walls, around 25% through windows and doors, 25% through the roof, and about 15% through the floor. This is why a heat loss analysis should be carried out when talking about energy efficiency [18]. Table 1 presents the required heat loads in the current building situation.

Table 1. Required heat loads in the current building situation.

Property		Amount
Total heat load [W]		9603
	from heat transfer [W]	*5108*
	from ventilation [W]	*4495*
Specific heat load [W/m^3]		44.5
Total area [m^2]		72
Total surrounding surface [m^2]		180
Total volume [m^3]		216
Form factor [1/m]		0.833
Heat transfer ratio [W/m^2]		0.58
Walls total area		162
Windows total area		18

The main heat loss (Q_T) is calculated by the formula (Eq. 1) and it should gather all values for the surrounding construction elements [19]:

$$Q_T = \frac{A}{R_0}(t_n - t_{a,c} - \Delta t_a)z_0, W \quad (1)$$

where:

A element area
R_0 thermal resistance of the element
z_0 coefficient depending on element’s orientation
$t_{a,c}$ calculated outside temperature
Δt_a outside temperature correction, based on element density
t_n air temperature

The calculations for heating losses according to the structural elements and room dimensions are shown in Table 2.

Table 2. Heating losses.

HEATING POWER REQUIRED									
Type – Industrial Building									
Heat Transfer Losses - ϕt. [W]									
Structural element	Dir. -	Thickness (mm)	Number (pcs.)	Length (m)	Height (m)	Area (m^2)	U, (Ueqv) (W/m^2 °C)	DT, (bu) (°C)	Φ_t, W
Room.101 Production hall troom.= 18 oC; Vroom.= 216 m^3									
External wall	N	292	1	12.00	3.00	17.98	0.676	34.0	413
Window	N	---	4	2.65	1.70	18.00	1.923	34.0	118
External wall	E	292	1	6.00	3.00	18.00	0.676	34.0	414
External wall	W	292	1	6.00	3.00	18.00	0.676	34.0	414
External wall	S	292	1	12.00	3.00	36.00	0.676	34.0	827
Ceiling	-	125	1	12.00	6.00	72.00	0.676	34.0	1654
Floor	-	150	1	12.00	6.00	72.00	0.262	34.0	209
Total losses ϕ_i=9603 W($\phi_{t,i}$=5108 W; V_{inf}=389m3; $\phi_{v,i}$=4495 W									
Total Heat Losses: 9603[W]									

The calculations were made with the help of specialized software for the calculation of heating and cooling loads in buildings, developed by S. Stamov. The software product is an extension of the one distributed with the assistance of KIIP (Chamber of Engineers in Investment Design) program for the calculation of heat losses and cooling load under Ordinance No. 15 on the technical rules and norms for design, construction, and operation of sites and facilities for production, transmission, and distribution of heat energy. This product meets the requirements of Ordinance No. 7 on the energy efficiency of buildings. During the experimental work, various combinations of heating methods and calculations are made for determining the energy efficiency of the developed system.

3.1. Heating with District Heating

Approximately 40% of the world-produced heat from district heating plants is used in the industry sector. Sometimes the users need high temperatures because of the production processes, which leads to reducing temperatures of distribution. Often heat pumps are used for increasing temperatures at local substations to help with the heat demand. Many networks are distributing heat by a pipe through pressurized water at high supply temperatures over 80°C, but a large number of losses occur (between 10% to 30%) in the most inefficient systems [20]. It is common for industrial buildings to use radiators connected to district heating for covering large spaces, since is relatively cheap. For achieving normal working conditions in terms of temperature at the experimental industrial site, four radiators will be needed with a power of 2650 W (Fig. 4)

3.2. Heating with Electric Heaters

Electric heaters work on the principle of convection, which is not very convenient in high spaces. They are equipped with a heating element installed in the lower part of the device. The air passing freely along it is heated and, following the laws of nature, rises up and leaves the device through special openings in the corps. The warm air is rising and the floor air stays cold, so more energy is needed to achieve good thermal conditions. Also, the cost of electricity significantly increases. It is important to note that for maximum efficiency of heating with convectors and reasonable electricity bills, it is necessary that the heaters are not turned off when there are no people in the room. When the room is empty, the temperature should simply be set lower than the one comfortable for the person, which will be maintained with minimal electricity consumption [21]. For the experiment, four electric heaters were counted with wall-mounting under the windows with a power demand of 2500W each (Fig. 5).

3.3. Heating with Air Conditioning

Air conditioning is defined as the treatment of the necessary air for achieving certain conditions of heating or cooling of air in a certain space [22]. Air conditioners often use a fan to distribute heated air in an enclosed space and improve thermal comfort as well as indoor air quality. Inverter technology provides optimal power control and efficient operation by changing the frequency of the power supply. Inverter air conditioners have electronic control, which ensures that the temperature and humidity levels in the room are always comfortable. Central air conditioning systems differ in the type of heat transfer fluid - direct evaporation (air) or water. Direct evaporation systems can be of the Variable Refrigerant Flow (VRF) type or rooftop. Central air conditioning systems using water are most often called chillers [23]. Even it is more popular for residential and commercial buildings it also can be used in industrial buildings. Because the consumption of energy is relatively high, it is not a very popular choice. For heating the experimental workspace, two air-conditioners are mounted on two parallel walls with a heat power capacity of 7,4kW (Fig. 6).

Table 3 shows the calculations of energy demand for the presented heating systems. For the infrared heaters, we use 8 hours working period because they must be switched on only when there are people in the room. The energy cost is set to average energy prices for January 2022.

Table 3. Energy consumption and costs for the different heating systems.

Property	Air-conditioning	Radiators	Electric heaters	Infrared heaters
Number of devices	2	4	4	2
The power demand for an hour [kW/h]	7.4	10.6	10	4
The power demand for 24 hours [kW]	177.6	244.4	240	32 (8 hours)
Energy cost [€]	42.6	12.81	58.42	7.79

It is clear that even with the use of modern technology for decreasing the energy consumption of appliances, the overall consumption of energy is high and expensive.

3.4. Heating with Infrared Heaters

For the selected working spaces, two infrared heaters with wall mounting are selected (Fig. 7). Their total power demand is 4 kW/h. Since they do not need to work thru the entire day, their consumption will be calculated only for the working hours (8h). This means that they will consume 32 kW and the total price for a day will be only 7,79 €.

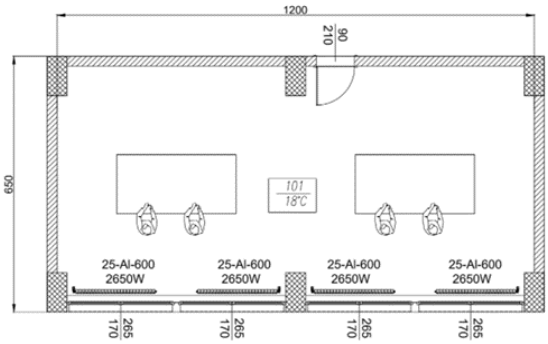

Figure 4. Heating with radiators

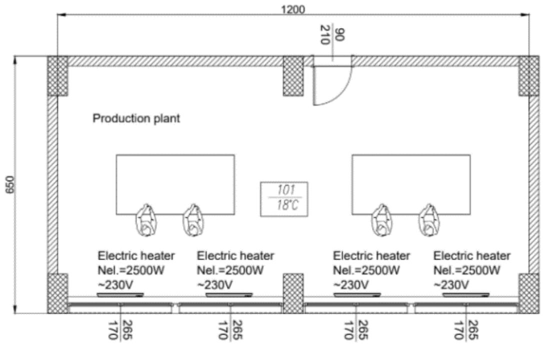

Figure 5. Heating with electric heaters.

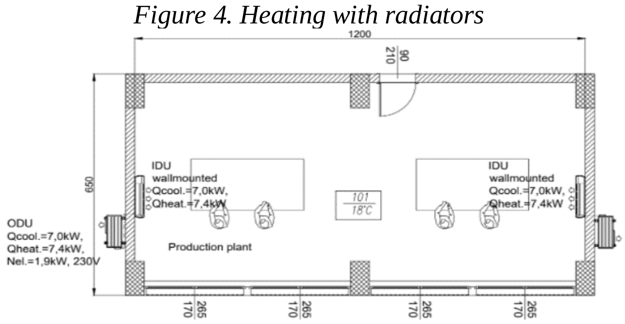

Figure 6. Heating with air-conditioning

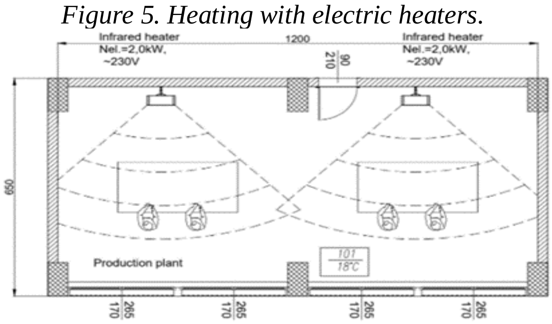

Figure 7. Heating with infrared heating

Those calculations include only the work of the heaters without integrating them into an intelligent control system.

4. CONTROL ALGORITHM FOR THE INTELLIGENT HEATING SYSTEM

The intelligent system is set to activate the heaters only when there are workers in the room. It also regulates the operating power of the heaters according to the room's temperature, the number of people, heat loss, and other parameters. The system uses fuzzy logic since the system can operate with any kind of input and provides efficient solutions to complex problems [24]. The logic and control of the output power are controlled by a fuzzy-logic controller (Fig. 8). This ensures maximum comfort and minimum energy consumption. The desired temperature and other parameters can be set remotely from the graphical interface, according to the feeling of the people/workers.

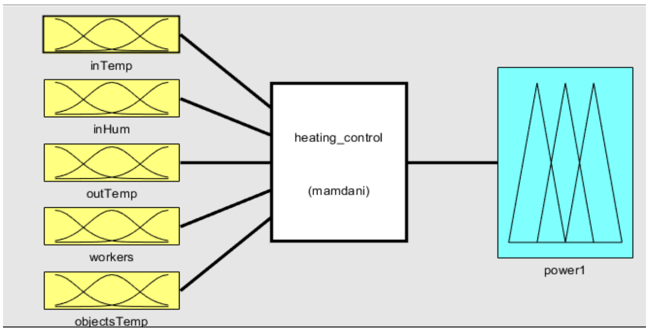

Figure 8. Fuzzy logic controller for infrared heating system.

The control and fuzzy logic algorithm are implemented as part of the web interface. All incoming data from the sensors are used as inputs to the fuzzy control. The output parameter from the controller is only one - power (set as a percentage of the maximum power). According to the determined power, the infrared heaters are switched on and off. At this stage of the research, the fuzzy control logic is based on five input parameters: room temperature and humidity, outdoor temperature, number of workers, and average temperature of all objects in the work area. These are the main components that significantly influence and determine the comfort of the work area. According to the specific influence of each of the input parameters, we also determine the behavior of the controller. Fig. 9 shows a graph for determining the power depending on the internal temperature and the temperature of the objects. The other dependencies defined in the logic of the fuzzy controller are presented in Figs. 10,11. Thus set, these dependencies determine the behavior of the controller under different input parameters.

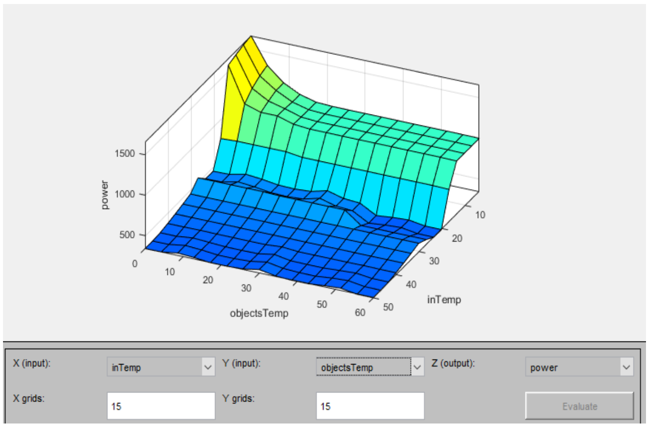

Figure 9. Dependences indoor temperature and temperature of objects.

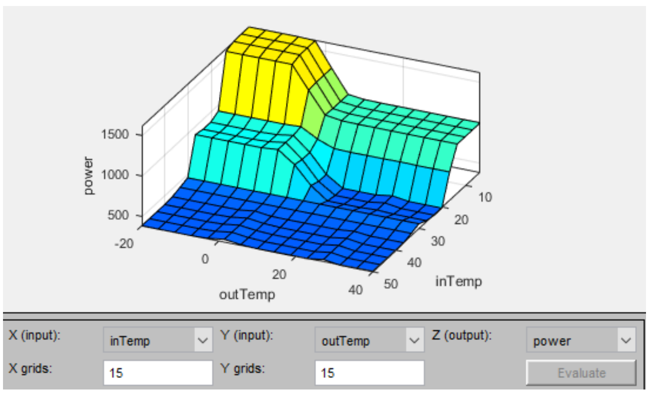

Figure. 10. Dependences on indoor and outdoor temperatures.

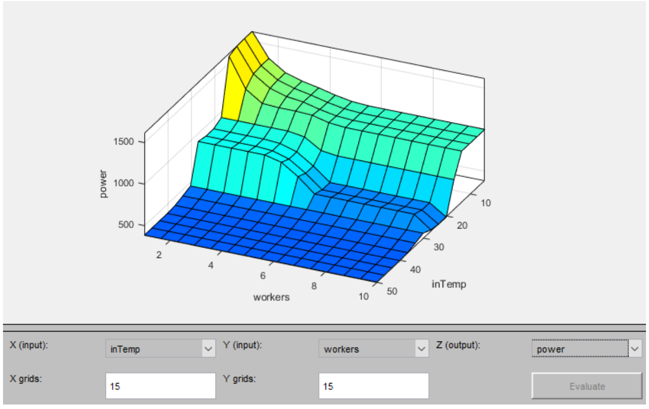

Figure. 11. Dependences on indoor temperature and number of workers.

The general overview of the algorithm for controlling the infrared heaters is presented in Fig. 12. To activate the system, the presence of workers in the work area must be detected.

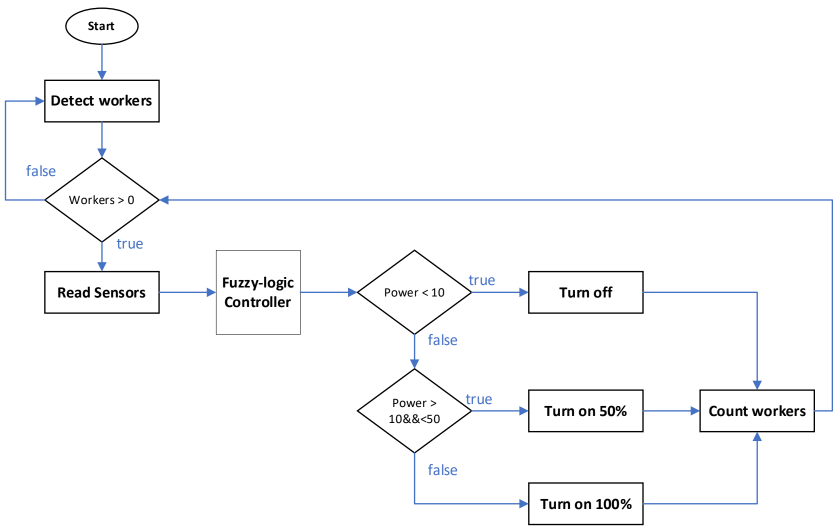

Figure 12. Block diagram of the system operation algorithm.

If the presence of workers is confirmed, the system is started and the data from all sensors is taken initially. This data is sent to the controller, which determines whether it is necessary to turn on the heating and to what extent. A heater activation threshold is set so that when minimum power is required, the heaters remain off. Reading data from the sensors is continuous as long as there are people in the room.

5. EXPERIMENTS AND RESULTS

The experiments were implemented in the simulation environment of Matlab - Simulink. Matlab is often used for creating simulation environments in energy-efficiency calculations [25]. In our simulation, the input data for outside temperature, number of workers and average temperature of the objects are fed through signal generators, changing them in different periods and thus a scenario is generated with all possible combinations. The indoor temperature in the room is measured by a simulated sensor and sent as feedback. The heating elements are controlled directly by a conditional "thermostat", which receives an assignment directly from the fuzzy logic controller. The overall simulation scheme is presented in Fig. 13. The system simulation is for a period of one week, with the room temperature set at 22°C. The main idea is to check what the energy consumption will be for this period and whether we can optimize the heating process.

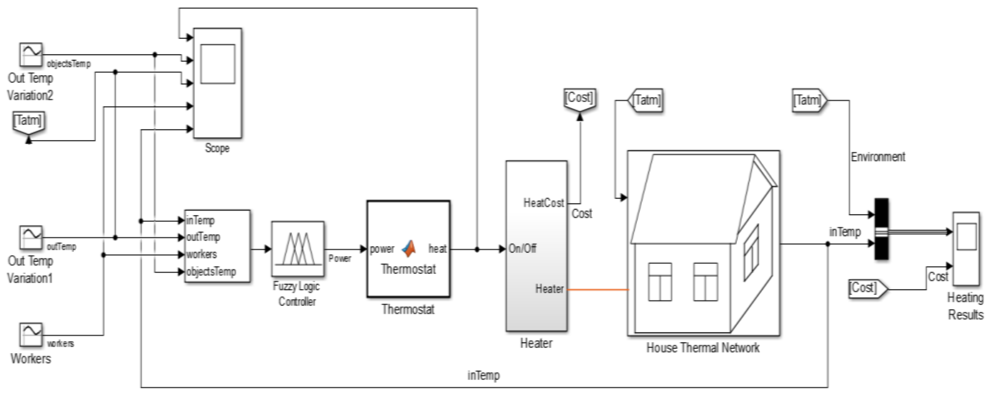

Figure 13. Simulation of the Intelligent system in Matlab.

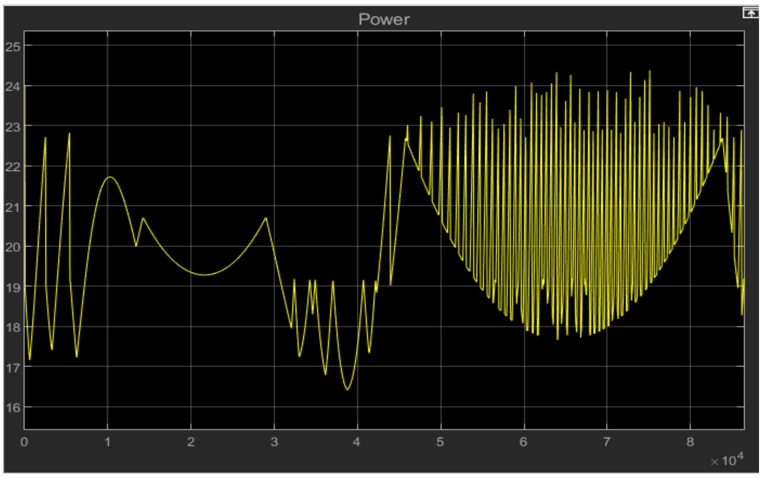

Figure 14. Results of the fuzzy-logic controller output signal.

Fig. 14 shows the output signal from the controller, which represents the required output power for a single heater in percentage (%). The set inclusion threshold is at 22%. It can be seen that for short periods of a few hours the heater is on. These experiments are from the system simulation. Fig. 15 shows a graph of the maintained indoor temperature, outdoor temperature and consumed electricity. It is obvious that the system is able to maintain normal temperature using minimum power.

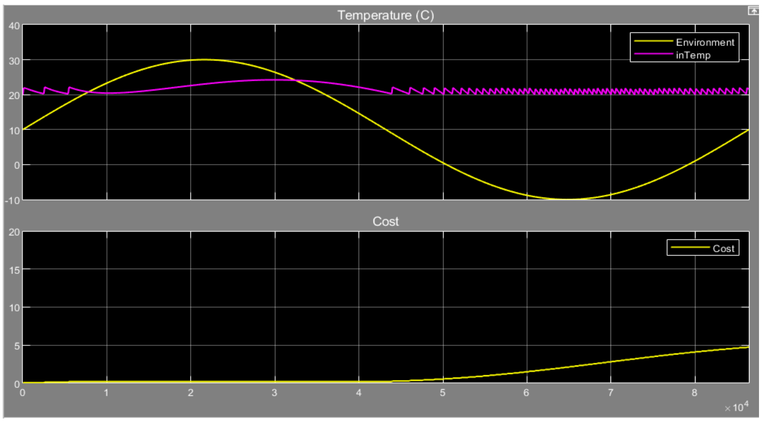

Figure 15. Results of the simulation system.

In addition, experiments of the system were performed in a real working environment. The results achieved are described below. After the application of the intelligent control system, the operating time of the heaters was reduced by an additional 45 min., because in the absence of people in the workroom, the system turns off the heating. This way the energy consumption lowers to a minimum of 29 kW. Additionally, after conducting experiments, it was measured that by increasing the room temperature and/or increasing the temperature of the objects in the room, the system reduces the power of the heaters and thus saves lower power consumption. During the operation of the system for a period of 4 hours, the consumption was recorded as follows:

- *Working in full power: 2 hours*
- *Working at 75% of the maximum power: 1 hour and 30 min.*
- *Working at 50% of the maximum power: 30 min.*

6. CONCLUSION

With the change in global energy demand and the development of renewable energy sources, scientists are looking for modern energy-efficient technologies for reduced energy consumption. Heating industrial buildings are part of the problem of energy efficiency, which, if solved, will drastically reduce energy consumption and costs. The challenges that are most often encountered in this type of building are large spaces, high ceilings, the opening of wide exterior doors, old construction, and more.

The article observes an intelligent system for heating industrial premises with infrared heaters. To prove its energy efficiency, a comparative analysis of the most commonly used technologies for this type of premises was made. When calculating heat loads and losses, it was proved that the existing heating solutions are too energy-intensive for this type of premises and lead to high expenses for users. Infrared heating on its part, due to its principle of operation, achieves lower energy consumption.

When such appliances are integrated into an intelligent control system, energy efficiency increases even more. By combining internet technologies, wireless communication and LoRaWAN technologies, effective intelligent control of this system has been achieved. These technologies use the reading and analysis of data from different types of sensors to achieve optimal performance of the devices. An additional advantage is that all processes can be monitored and controlled remotely, which involves controlling the temperature and operation of the system from anywhere in the world via the Internet. A series of experiments proved that the developed system can successfully improve the heating results in industrial buildings. This way good working conditions can be maintained and the work of the heaters can be monitored and controlled from a distance. The integration of such systems in industrial buildings, tailored to the type of production and work processes, can significantly reduce energy consumption for heating and increase energy efficiency in this sector.

Acknowledgment

The paper is partially supported and financed by the National Science Fund of Ministry of Education and Science of the Republic of Bulgaria, by Project for junior basic researchers and postdocs – 2019, Contract № КП-06-М37/2 from 06.12.2019.

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