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## MODELING OF OPERATING MODES OF INDUSTRIAL HEATING, VENTILATION AND AIR CONDITIONING

*In this work elaborated model of heating, ventilation and air conditioning (HVAC) system, carry out simulation of different modes of operating, assessment and optimization of consumption electric and heat energy. Given understanding and problem of HVAC system as important influence factor on energy demand, also it is need to mention that research in that field requires a lot of knowledge in different fields of science. Due to regression analyses were done to find a model of system to estimate the accuracy in comparison with real HVAC system, it was based on LabView, MATLAB Simulink and OpenModelica simulation tools. This work consider HVAC system, development from system a model which basically can be described by internal elements like fan, heater, air piping and etc. Also it will be found new strategies to achieve optimal regulation for such system, which allow to confirm the best decision depending on multivariable changing dynamic model. Introduced and considered standard feedback system built on PI controller. Simulation results show possibility of significant energy savings and comfort enhancement using the proposed strategy at different operation modes. Carried out economic assessment of modified technology implemented in PI controller like part of start-up project. Develop recommendations in exploitation of such systems. The results can be utilized to estimate the energy demand for HVAC system at different times of year, which would contribute to improving the accuracy of prediction automatic devices.*

**Keywords:** heating, ventilation, conditioning, HVAC systems, optimization of modes of operation, energy saving, energy efficiency.

**Introduction** Energy saving in the company begins with a clear understanding of the leadership of the need to improve the economic performance of the company due to lower energy consumption per unit of production. Ventilation and air conditioning is a significant component of the overall balance of FER consumption, which accordingly requires attention to energy conservation and energy efficiency, as these consumers have significant potential for energy conservation.

Recently, with the adoption of new standards for climatic conditions inside industrial and other buildings, in the future more and more ventilation (HVAC) systems will be installed. Very often ventilation units operate in constant mode with the maximum power, when it is not even necessary, and the presence of automation on this equipment is very rare.

Often, ventilation units operate with variable environmental characteristics, with a probable distribution of pressure, temperature and air flow, the design of such systems usually occurs in stationary conditions of the environmental parameters. Therefore, there is a need to identify the optimal modes of operation when changing the load characteristics.

**Formulation of the problem** Due to the further increase in the number of ventilation (HVAC) systems and the increase in air regulation, there is an urgent need to optimize the operating modes of ventilation equipment. Electricity consumption by ventilation units is significant as most of the latter are outdated and operate not in energy-efficient modes. On the basis of the simulation of the installation it is possible to identify the most rational modes for one or another type of load using the methods of forecasting power consumption and its adjustment by means of automation.

**Analysis of recent research** Mostly all scientific works which are dedicated to optimization of different types of HVAC systems were carry out by foreign publications, basically it based on developing models both static and dynamic for commercial building sector (Yohei Yamaguchi, Yusuke Miyachi), imperial modelling and gradient projection optimization (V. Vakiloroaya, B. Samali), additionally considered influence of natural ventilation with HVAC system (Raad Z. Homod, Haider A.F. Almurib)

**Purpose and objectives** The purpose of the research is developing a model of the ventilation installation, modeling the operating modes of the installation for different types of load (constant and alternating), which has uncertainty and requires different methods for predicting energy consumption. The objective of the study is to

identify the optimal mode of operation of the installation based on the use of automation (controller) for prediction of consumption and management of the installation.

**Materials and methods** The methods used are based on a correlation-regression analysis, which allows to determine the most important factor characteristics, also for modeling were used OpenModelica software, LabView software and methods from the general theory of optimization and decision-making theory were used.

**Main research material** The major components considered in the system model are: an air-conditioned room of industrial unit and air-handling unit (AHU), which consists of a fan, cooling and dehumidifying coil, heating coil, humidifier, filter and air-piping. Simple HVAC model block diagram can be observed in figure 1 and simulation model in figure 2.

In summer operation season, hot and humid air enters the cooling and dehumidification coil in the AHU. The air temperature reduces when air goes through coil and water vapour is condensed, which produces an effect in decreasing relative humidity. In the zone, the thermostat senses the temperature of the zone and gives signal to the controller unit to produce input to the chiller to change flow rate of water supplied to the cooling coil. For winter season of operating, often dry and cold air goes in the AHU. The sensor senses the temperature in main space and sends a signal to the controller, which uses the error signal to control the input temperature of the water flows through the heating coil.

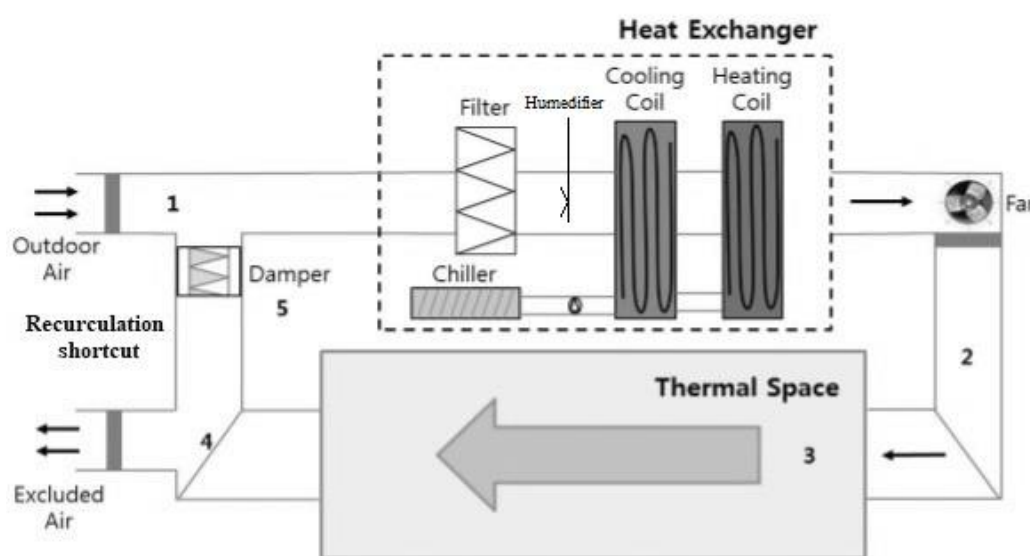


Figure 1 - Simple block diagram of conventional HVAC system

In industrial application of such systems in many cases we have some pollutant in main working area and we have limitation on the concentration of pollutant due to sanitary hygiene requirements. Also pollutant mass flow can be represented as some function of time during the working day and can be approximated by experimental data. If we assume that in room (figure 1 - thermal space) present some source of pollution (p) with mass flow rate like generation  $\dot{m}_{p,g}$  and air in room is homogeneous mixture (perfect mixing), so that the zone temperature distribution is uniform and the dynamics of the zone can be expressed in simple capacity we have such equation (1) for mass balance of pollutant:

$$\frac{dm_p}{dt} = \dot{m}_{p,in} - \dot{m}_{p,out} + \dot{m}_{p,g} \quad (1)$$

where  $m_p$  - mass of pollutant in room, kg;  $\dot{m}_{p,in}$  - inflow air with some amount of pollutant, kg/s;  $\dot{m}_{p,out}$  - effluent air with pollutant, ks/s;  $\dot{m}_{p,g}$  - generation of pollutant in air in room, kg/s.

Also mass balance law for pollutant can be rewritten in terms of parameter of air:

$$\frac{dm_p}{dt} = \dot{V}_{air,in} \cdot (c_{p,in} - c_{p,out}) + \dot{m}_{p,g} \quad (2)$$

where  $\dot{V}_{air,in}$  - inflow volume of air in room, m<sup>3</sup>/s;  $c_{p,in}$  - concentration of pollutant in inflow air, mole/m<sup>3</sup> of pure air;  $c_{p,out}$  - concentration of pollutant in effluent air, mole/m<sup>3</sup> of pure air.

At steady state  $\frac{dm_p}{dt} = 0$  condition eq.2 can be also written in such way:

$$\dot{V}_{\text{air,in}} = \frac{\dot{m}_{p,g}}{M_p c_{p,r}} \quad (3)$$

where  $M_p$  - molar mass of pollutant, kg/mole;  $c_{p,r}$  - concentration of pollutant inside in the room equal to  $c_{p,\text{out}}$ , mole/m<sup>3</sup>.

For heating air by using heater based on hot water which given by eq.(3) (it was neglected heat losses to environment due to small value and assumed high heat conductivity of tubes so thermal resistance neglected). Also heat transfer coefficient for convection assumed to be constant value because of low speed changes of air flow as result of controlling fan's speed of rotating :

$$\dot{Q}_H = \hat{c}_{\text{air}} \dot{m}_{\text{air}} (T_r - T_{\text{out}}) \cdot (1 - \eta_{\text{rec}}) = \alpha_{\text{HE}} (T_{\text{tube}} - T_{\text{in}}) A_{\text{HE}} \quad (4)$$

where  $\dot{Q}_H$  - heat transfer by heat exchanger, kW;  $H_{\text{air}}$  - enthalpy of air at selected moment of time, kJ;  $\hat{c}_{\text{air}}$  - specific heat capacity of air, kJ/kg;  $\dot{m}_{\text{air}}$  - mass flow of air in heat exchanger and out, kg/s;  $T_{\text{out}}, T_{\text{in}}$  - inflow and outflow temperature of air, °C;  $\alpha_{\text{HE}}$  - heat transfer coefficient for convection, kW/(°C m<sup>2</sup>);  $A_{\text{HE}}$  - heat transfer area of heat exchanger, m<sup>2</sup>.

Under the above assumptions, heat balance equations of the zone are:

$$\hat{c}_{\text{air}} m_{\text{air,r}} \frac{dT_r}{dt} = \dot{V}_{\text{air,in}} \rho_{\text{air}} \hat{c}_{\text{air}} (T_{\text{in}} - T_r) - \sum U_i \cdot A_i (T_r - T_i) + q(t) \quad (5)$$

$$\hat{c}_w m_w \frac{dT_w}{dt} = U_w A_w (T_r - T_w) - U_w A_w (T_w - T_{\text{out}}) \quad (6)$$

$$\hat{c}_{\text{roof}} m_{\text{roof}} \frac{dT_{\text{roof}}}{dt} = U_{\text{roof}} A_{\text{roof}} (T_r - T_{\text{roof}}) - U_{\text{roof}} A_{\text{roof}} (T_{\text{roof}} - T_{\text{out}}) \quad (7)$$

where  $m_{\text{air,r}}$  - mass of air in room (constant value due to assumption that thermal expansion of the air is negligible and inflow and outflow of air is equal), kg;  $T_r$  - temperature of air in room, °C;  $\rho_{\text{air}}$  - density of air assumed to be always constant 1,2 kg/m<sup>3</sup>;  $U_i$  - heat transfer coefficient for heat losses  $i$  part of room (wall, roof, infiltration), kJ/(m<sup>2</sup>\*K);  $A_i$  - area of  $i$  part of the room, m<sup>2</sup>;  $T_i$  - temperature of  $i$  part at internal side in the room, °C;  $q(t)$  - additional heat flow by another sources (humans, lamps, insolation), kW.

Equation 6 describes the thermal inertia of building by heat capacity of the wall where subscript w means wall and  $T_{\text{out}}$  is temperature outside of building.

Next part of model is cooling device or refrigerator part also with heat exchanger and be described by cooling cycle (figure 3). For model description was taken R22 as the most common agent for cooling with equation for description:

$$\dot{Q}_C = \dot{m}_{\text{R22}} \cdot \varepsilon \cdot W \cdot (1 - \eta_{\text{rec}}) \quad (8)$$

where  $\dot{Q}_C$  - heat flow of cooling the air in heat exchanger of cooling device, kW;  $\dot{m}_{\text{R22}}$  - mass flow of cooling agent due to work of compressor, kg/s;  $\varepsilon$  - cooling coefficient;  $W$  - specific work of compressor, kJ/kg.

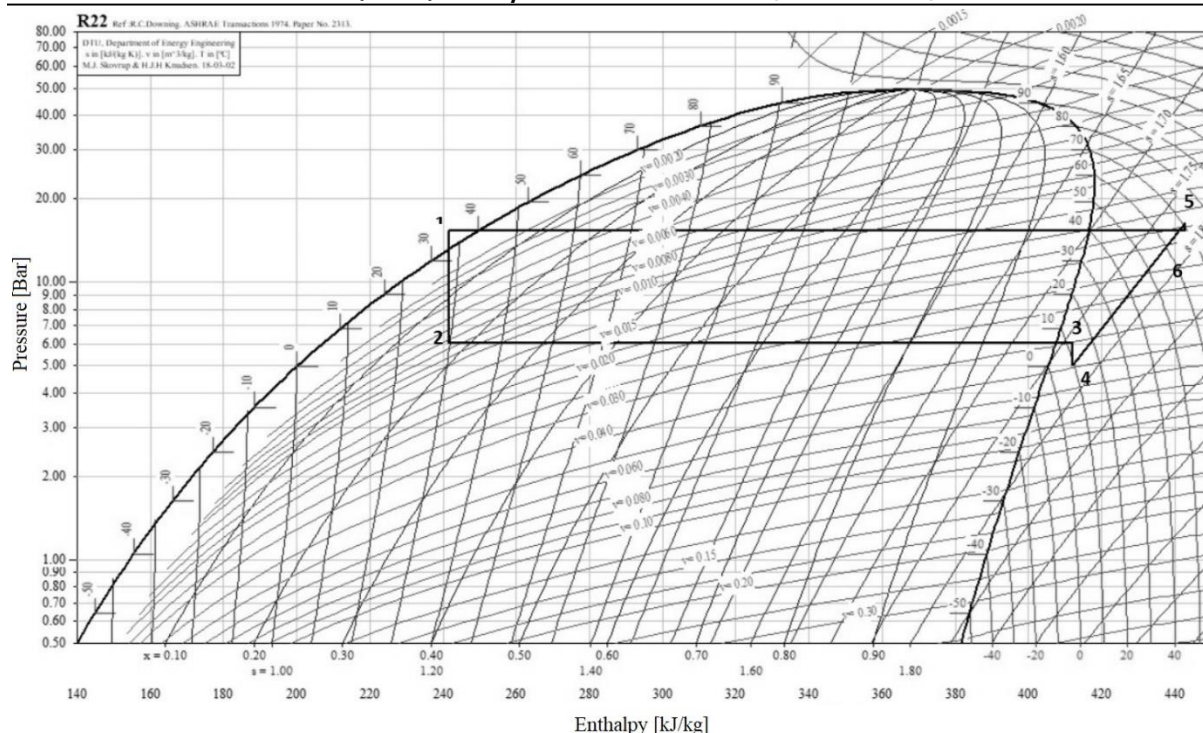


Figure 2 Cooling cycle of air cooling device

In case of using recuperation we have the heat transfer of air streams in air-conditioning system and we assumed that it occurs under steady and adiabatic conditions and without frictional losses. So as was mentioned that inflow  $\dot{V}_{air,in}$  and outflow  $\dot{V}_{air,out}$  of air in the room is the same value:

$$\dot{V}_{air,in} = \dot{V}_{air,out} \quad (9)$$

The fan's power consumption at not steady state conditions can be approximated as regression equations for absolute value of pressure  $p_v(\dot{V}_{air,in})$  and efficiency coefficient for fan  $\eta_v(\dot{V}_{air,in})$  under some interval allowable  $\dot{V}_{air,in}$  values, so basically it is enough to use 2<sup>nd</sup> order regression equations (coefficients  $a$  can be evaluated due to least square method) to evaluate power consumption of fan:

$$\dot{W}_v = \frac{(a_0 + a_1 \cdot \dot{V}_{air,in} + a_2 \cdot (\dot{V}_{air,in})^2) \cdot \dot{V}_{air,in}}{a_3 + a_4 \cdot \dot{V}_{air,in} + a_5 \cdot (\dot{V}_{air,in})^2} \quad (10)$$

where  $0,15 \cdot \dot{V}_{air,max} < \dot{V}_{air,in} < \dot{V}_{air,max}$ .

Firstly, it was modeled the simplified model without any automatic devices at winter condition with temperature of the outside air at -1 °C, with rate of heating the outdoor air calculated from heat losses at -1 °C with constant air flow and respectively constant heat flow. The result of simulation for simplified model was done at OpenModelica tool (Figure 3) to find model correctly developed and verified what a time constant for building (room) is.

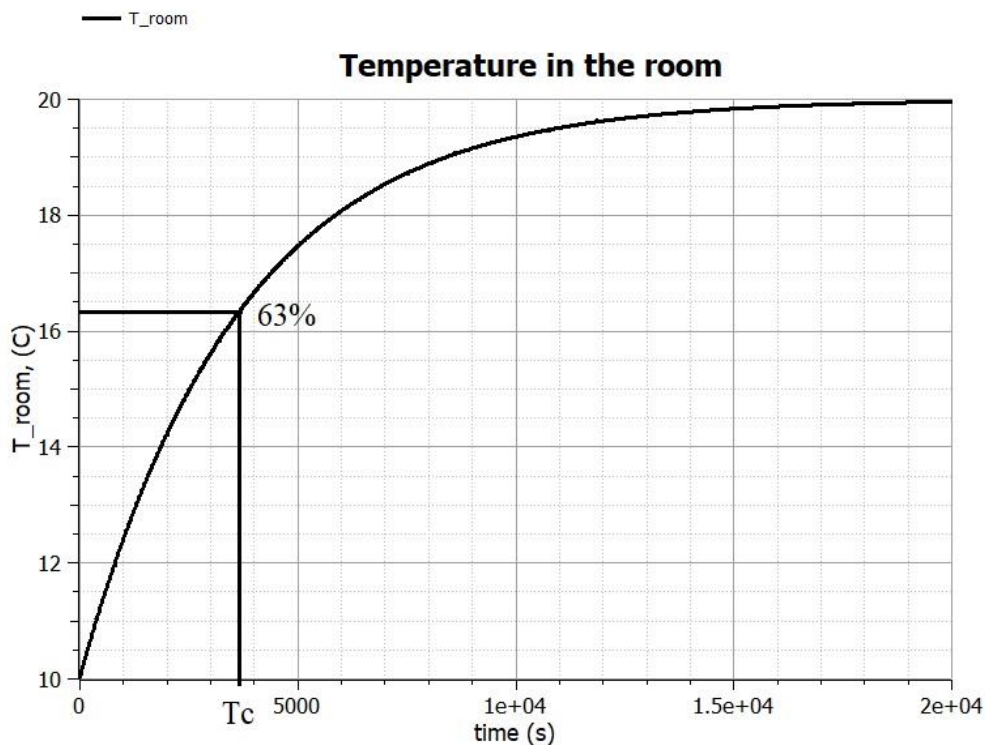


Figure 3 - Change of the temperature in the room with initial condition 10 °C with outdoor temperature -1 °C with simulation in OpenModelica tool

More complicated case was studied in MATLAB with meaning of more dynamic model with setting parameters of model to be a function of time or some circumstances (figure 4).

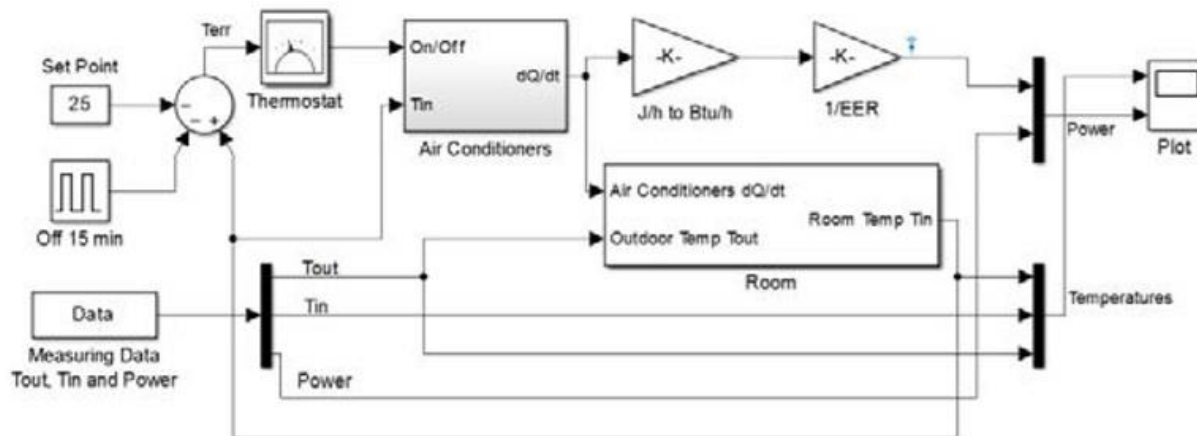


Figure 4 - Mathematical model of HVAC system in MATLAB

After curve fitting in MATLAB of experimental data we get next figure 5 for  $p_v(\dot{V}_{air,in})$  and  $\eta_v(\dot{V}_{air,in})$  accordingly.

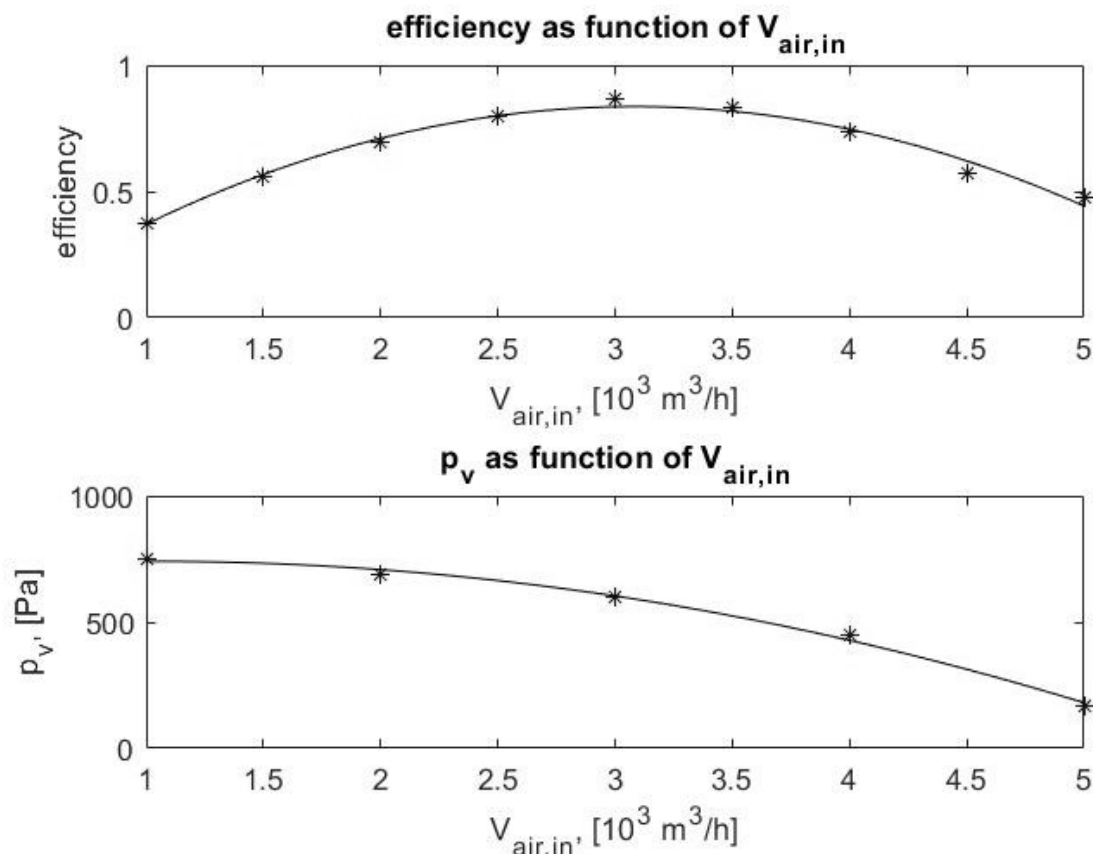


Figure 5 - Polynomial values of ventilator efficiency and pressure from regression approximation in comparison with experimental data

The result of simulation simple HVAC model is used to approximate energy required for cooling thermal space (room) at temperature set point 25 °C (Table 1).

Table 1 - Comparison between the model simulation result and measurement results at 25 °C during time interval 120 min.

	Measured values			Simulated values		Differences	
	$T_{out,av}$ (°C)	$T_{in,av}$ (°C)	Energy (kWh)	$T_{in,av}$ (°C)	Energy (kWh)	$T_{in,av}$ %	Energy %
Mode 1	26,5	23,3	11,2	23,2	13,5	0,42	23%
Mode 2	27,1	24,1	11,7	24,6	12,8	2,07	13%
Differences	2,2%	3,3%	2,6%	5,6%	5,34%		

**Conclusions** In this paper, we have addressed the modelling and optimization problem of simple HVAC system to target energy savings and verified the proposed approach [3]. By using the monitored data, mathematical models for the set-up components are developed and implemented in a transient simulation of the integrated system operating in various conditions. Results showed that by applying this approach, an air-cooled central cooling plant HVAC system can achieve significant improvements in energy-efficiency and performance, especially in part-load conditions.

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## **МОДЕЛЮВАННЯ РЕЖИМІВ РОБОТИ ПРОМИСЛОВОГО ОПАЛЕННЯ, ВЕНТИЛЯЦІЇ ТА КОНДИЦІОНУВАННЯ ПОВІТРЯ**

*У роботі розроблена модель системи опалення, вентиляції та кондиціонування (СВіК), проводяться симуляція різних режимів експлуатації, оцінка та оптимізація споживання електричної та теплової енергії. З огляду на розуміння та проблеми системи вентиляції та кондиціонування як важливого фактору впливу на споживання енергії, також слід зазначити, що дослідження в цій галузі вимагає значних знань у різних галузях науки. Завдяки регресійному аналізу було зроблено пошук моделі системи для оцінки точності у порівнянні з реальною системою СВіК, яка базується на інструментах моделювання LabView, MATLAB Simulink та OpenModelica. У цій роботі розглядається система вентиляції та кондиціонування, визначення меж системи, на основі якої відбувається розробка моделі, яка в основному може бути описана внутрішніми елементами, такими як вентилятор, нагрівач, повітряні трубопроводи тощо. Також буде знайдено нові стратегії для досягнення оптимального регулювання для такої системи, що дозволяє досягти кращих енергетичних показників у залежності від багатоваріантної зміни динамічної моделі. Введена і розглянута стандартна система зворотного зв'язку, побудована на ПІ-контролері. Результати моделювання показують можливість істотної економії енергії та підвищення комфорту, використовуючи запропоновану стратегію в різних режимах роботи. Проведено економічну оцінку використання модифікованої технології, впроваджені в контролері ПІ, як частина старт-ап проекту. Розроблено рекомендації щодо експлуатації таких систем. Результати можуть бути використані для оцінки енергетичного попиту на системи вентиляції та кондиціонування в різні періоди року, що сприятиме покращенню точності автоматичних пристроїв при прогнозуванні енергоспоживання.*

**Ключові слова:** опалювання, вентиляція, кондиціонування, системи кондиціонування повітря, оптимізація режимів роботи, енергозбереження, енергоефективність.

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