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Effects of Uncertainty on the Prediction of Energy Consumption of Compressed Air Systems

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Abstract

Compressed air is an essential part of operations at many industrial and manufacturing plants. For example, compressed air can be used for stamping, clamping, driving power tools, cleaning tools, and powering controls or actuators. Simulink is used to model a continuously operating compressed air system, aftercooler, and heat-rejection system. The three main sources of energy consumed by the system include the energy consumed by the air compressor's motor, the energy consumed by the aftercooler's pump, and the energy consumed by the heat-rejection system's fan motor. Testing agencies test equipment per a standard and document performance results. Regulatory-governmental-agencies select a testing standard and a minimum performance rating. Regulatory agencies allow the manufacturers to advertise and sell their products if, during testing, product performance stays within an allowable tolerance. A typical acceptable tolerance for compressor airflow is between ± 4% and ± 7%, depending on the compressor's capacity,

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meanwhile, according to the ASHRAE 90.1, section G, the typical acceptable tolerance for the pump's waterflow rate is ± 5% of its rated value. Finally, the acceptable fan tolerance is between ± 3% and ± 5% of its rated value. Also, all other equipment in the plant has its own designated tolerances. These tolerances introduce uncertainty in predicting the overall system's energy consumption. The authors have used the compressor airflow's allowable tolerance in their compressed air model to evaluate the effects of this uncertainty on a compressed air system's predicted yearly energy consumption.

Keywords: *Compressed air systems; energy consumption; energy efficiency; energy saving; simulation modeling; Simulink.*

I. INTRODUCTION

Compressed air systems are one of the most important systems in the operations at many industrial and manufacturing facilities across various industries. Energy management and how to effectively deal with it in general have become important in recent years. It has been found that most of the energy consumption and energy waste inside these facilities takes place in the compressed air systems. It has also been found, during energy-assessment activities for the Industrial Training and Assessment Center (ITAC) of the United States Department of Energy that the majority of energy savings that achieved for various industrial facilities has come in from making their compressed air systems more efficient [1-3].

Because of that reality, a longtime topic of interest has been predicting these systems' energy consumption. Numerous articles and research papers have been published with the goal of both shedding more light on this subject and educating facility and maintenance engineers, helping them to better understand their compressed air systems and how to manage and maintain these systems during operations most effectively. These publications have also been critical to helping these personnel maximize the energy efficiency and productivity of their compressed air systems during operations. These publications also helped them increase performance, productivity, and be more efficient in energy consumption and achieve energy efficiency. Maxwell and Rivera [4] have focused on developing dynamic system modeling, running different energy-use simulations to provide an analytical tool for evaluating the performance of these systems under a variety of operating conditions and control strategies. Schmidt and Kissock [5] estimated energy savings from energy conservation retrofits in compressed air systems from air use reduction and other changes. Thabet et al. [6] introduced the idea of using intelligent systems to reduce energy consumption and increase efficiency in compressors by considering real-time circumstances, artificial intelligence (AI), and predicted needs. Widayati and Nuzahar [7] conducted a research within the food industry explaining a technique for compressed air system optimization that determines the optimal conditions for compressors operation, while also evaluating energy needs to improve operating efficiencies, increasing energy savings and lowering costs. Schmidt and Kissock [8] presented a methodology that featured case-study examples, using easily obtainable performance data and rule-of-thumb methods, for modeling air compressor performance to calculate the projected energy savings. Hernandez-Herrera et al. [9] analyzed and calculated several main energy efficiency measures that can be applied to compressed air systems as necessary tools for companies that want to reduce energy consumption. Hessmer et al. [10] provided comprehensive information complied from technical reviews and scoping studies carried out at industrial facilities, in which energy efficiency upgrades had been made to the compressed air systems. Mousavi et al. [11] presented an overview of techniques used to model energy consumption as well as various approaches to controlling compressed air systems and to demonstrating the system’s energy consumption dynamics.

In this research, the authors take a novel approach in predicting overall energy consumption for compressed air systems in manufacturing facilities. According to the U.S. Department of Energy’s test procedures for compressor final rule (DOE 2016, 216) [12], a typical acceptable tolerance for compressor airflow is between ± 4% and ± 7%, depending on the compressor’s capacity. According to ASHRAE 90.1, section G (ASHRAE 2019) [13], the typical acceptable tolerance for the pump’s waterflow rate is ± 5% of its rated value. Finally, the acceptable fan tolerance is between ± 3% and ± 5% of its rated value (AHRI 2016, 4) [14]. Also, all other equipment in the plant has its own designated tolerances. Usually, these tolerances are not taken into consideration when predicting energy consumption within a feasibility or scope studies pertaining to the installation of any new project or when predicting operational costs for a given industrial facility. In this research, the authors study the effects of uncertainty on the airflow of compressed air systems across a year. A compressed air system model was developed and employed utilizing MATLAB Simulink, to evaluate its impacts in predicting total energy consumption and costs for the integral compressed air system. The hourly temperature variation across all of 2021 in Atlanta, Georgia, USA, was also considered, to optimally predict total energy consumption for the entire system per annum based on an hourly study. The results of this study will help different stakeholders and managers develop accurate studies to better estimate costs when they want to install a new system or upgrade an existing one. It provides a way to help facility managers more accurately predict energy consumption for their compressed air systems.

II. COMPRESSED AIR SYSTEM MODEL

In this paper, a simulation for a compressed air system model was developed utilizing MATLAB Simulink based on thermodynamics, heat transfer, and fluid mechanics theories. A visualization of a real compressed air system of a certain industrial process that requires a steady amount of 0.5 kg/sec supply of compressed air at a required pressure of 500 kPa and a maximum temperature of 30 °C was prepared at the beginning. This compressed air system consists of a) an Isentropic compressor with an efficiency of 80 % that compresses a certain amount of air at local ambient conditions (100 kPa pressure, and current ambient temperatures) into the required operating pressure, b) a cooler acting as a cross-flow heat exchanger to reduce the temperature of the air merging from the compressor to no higher than the required maximum temperature of 30 °C in the system, c) a water pump that provides the required amount of cooling water, from a cooling tower, needed for the heat-exchange process, and d) a cooling tower that reduces the temperature of the hot water emerging from the heat exchanger post-heat-exchange process. Figure 1 below shows visualization of the compressed air system, including its various components.

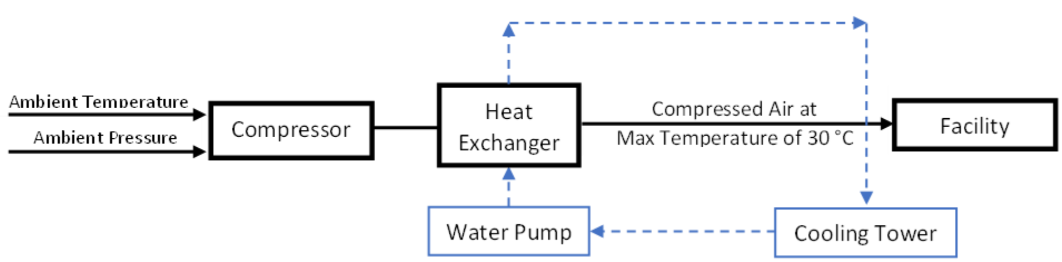


Figure 1: Visualization of the compressed air system used in the simulation.

Modeling for the compressed air system consists of engineering formulas and mathematical equations that build the system and connect its various components, as explained later in this paper.

Each physical component in the above compressed air system visualization was modeled using several blocks in SIMULINK.

In the SIMULINK modeling, each block performs a specific process. The blocks are also arranged in the same order as the flow of mathematical equations used to solve the engineering formulas that render the results for each physical component (compressor, heat exchanger, water pump, and cooling tower) within the integral compressed air system. Each block in the model has input and output data; these sets of input data represent numbers tied to each physical component in the compressed air system or pull from results from the previous operation of the model, while the output data are the results of the specific processes of each block in Simulink.

A. *Compressor Model*

The air compressor modeling begins by identifying the thermodynamic operations required to obtain the required operating pressure of 500 kPa and the actual temperature leaving the compressor. Fundamental equations governing these operations are shown in Eqs. (1) to (5). The ambient atmospheric pressure of 100 kPa represents these equations' first input data. The second input data represent the acceptable mass flow rates of the air that would be compressed by the compressor. The last input data are the ambient temperatures. In this paper, the actual variation of ambient temperature per hour throughout the year of 2021 were used rather than assuming a fixed or input temperature at any moment. Detailed temperature data for Atlanta, Georgia, USA, for every hour of the normal business day (8:00 a.m.-8:00 p.m.) in 2021 of most of the area's industrial facilities were obtained from the World Weather website [15] and were used as input data for the fundamental mathematical equations governing the entire model during simulations.

$$\mathrm{T_{2s}} = \mathrm{T_1}\left(\frac{\mathrm{P_2}}{\mathrm{P_1}}\right)^{\frac{\mathrm{k}-1}{\kappa}} \tag{1}$$

$$\mathrm{W_{cs}} = \mathrm{C_p}(\mathrm{T_1} - \mathrm{T_{2s}}) \tag{2}$$

$$\eta_\mathrm{s} = \frac{\mathrm{W_{cs}}}{\mathrm{W_c}} \text{ so that } \mathrm{W_c} = \frac{\mathrm{W_{cs}}}{\eta_\mathrm{s}} \tag{3}$$

$$\dot{W} = \dot{m}\, W_c \tag{4}$$

$$W_C = \dot{m} C_p (T_1 - T_2) \tag{5}$$

where:

P_1: Input ambient pressure.

P_2: The required operating pressure.

T_1: The hourly input temperatures.

T_2: The actual temperature leaving the compressor.

$\dot{W}$: Power required to drive the compressor.

These equations are modeled using SIMULINK blocks in the correct order to model the compressor component's performance only within the integral compressed air system.

B. Heat Exchanger Model

Since air is coming out from the compressor at a high temperature, an effective cooling process through a suitable heat exchanger is necessary to reduce this temperature and maintain a maximum operating temperature of 30 °C, for safe operations within the facility. A suitable cross flow heat exchanger that uses coolant water has been selected for the cooling process. This heat exchanger has a surface area of 240 m^2, a heat transfer coefficient (U) of 225 $W/m^2 \cdot k$., and an efficiency (Є) of 94 %. Cooling water enters the heat exchanger at 16° C with a c_p of 4.186 kJ/kg·K, and it will be cooled down using a cooling tower and an appropriate water pump after emerging from the heat exchanger at a high temperature. Our heat exchanger modeling began by identifying the heat transfer operations required to design an effective heat exchanger. The fundamental relations governing these operations are shown below:

Step 1: Determining $C_{\min}$ between $C_{air} = \dot{m}\, c_p$ of air and $C_{water} = \dot{m}\, c_p$ of the cooling water (6);

Step 2: Using a heat exchanger efficiency (Є) of 94 %;

Step 3: Calculating $q_{act} = \epsilon \times C_{\min} \times (T_{hi} - T_{ci})$ to get the heat transfer rate between the entering hot air emerging from the compressor and the entering cold water to the heat exchanger (7); and

Step 4: Using the same heat transfer rate calculated from Step 3 to calculate the air temperature leaving the compressor ($\boldsymbol{T_{ho}}$) from Eq. (8):

$$q_{act} = \epsilon \times C_{\min} \times (T_{hi} - \boldsymbol{T_{ho}}) \tag{8}$$

These steps are modeled later using SIMULINK blocks in the order to model the compressor component only within the entire compressed air system.

C. Open-Circuit Heat-Rejection Model and Total Power Required for the System

It is necessary to provide the system with a cooling tower and a water pump to keep the cooling water used in the heat-exchange process low, at 16° C, after it emerges from the heat exchanger. An efficient cooling tower and an appropriate water pump were selected to achieve this process after doing the required calculations for the cooling capacity needed. The actual heat to be removed from the air compressor by the heat exchanger was obtained at the beginning from Step 4. According to ASHRAE 90.1, section G.3.1.3.11 (ASHRAE 2019, 317) [13], any open-circuit heat-rejection system works between 83° F and 93° F (33.9° C and 28.3° C) as a standard operation set point with ΔT_{water} = 5.6 °C. The mass-flow rate of cooling water used in the heat-rejection system, $\dot{m}_{water}$, with the unit of kg/sec was subsequently calculated from the following equation:

$$\dot{m}_{water} = \frac{\dot{Q}_{water}\ or\ q_{act}}{c_{p-water} \cdot \Delta T_{water}} \tag{9}$$

Then the $\dot{m}_{water}$ was converted to GPM. Based on section G3.1.3.11 of ASHARAE 90.1 (ASHRAE 2019, 317) [13], the maximum fan power for heat-rejection equipment shall have an efficiency of 38.2 gpm/hp. Therefore, the fan power, P_{fan}, was subsequently calculated from Eq. (10):

$$P_{fan} = \frac{\dot{m}_{water}}{38.2} \tag{10}$$

Based on the same section of the ASHRAE 90.1 (ASHRAE 2019, 317) [13], the maximum pump power input should be 19 W/gpm. Therefore, the total pump power, P_{pump}, was calculated based on Eq. (11),

$$P_{pump} = 19\ \dot{m}_{water} \tag{11}$$

Modeling for the open-circuit heat-rejection system was performed based on these functions on SIMULINK. Meanwhile, total power required for the integral compressed air system was easy to predict from the final modeling on SIMULINK, based on the power required to drive the compressor (5), the fan power required in (10), and the total pump power (11).

III. COMPRESSED AIR SYSTEM SIMULATION

A reliable model, which would later be effectively utilized, was prepared for the next phase of simulations and results. According to Table 1 in the U.S. Department of Energy's test procedures for compressor final rule (DOE 2016, 216) [12], a typical acceptable tolerance for compressor airflow of is between ± 4% and ± 7%, depending on the compressor's capacity. It was found, based on the current mass flowrate of air ($\dot{m} = 0.5\ \mathrm{kg/s} = 415.28 \times 10^{-3}\ \mathrm{m}^3$ / sec) utilized in this research, that the acceptable tolerance in airflow is ± 4%. A simulation in Simulink has been run on 25 different random values of the ($\dot{m}$) in a range of ± 4 %. MS Excel's "Random" function was used between 0.48 kg/s and 0.52 kg/s to get the 25 random values of $\dot{m}$. These values were then used in the simulation phase on SIMULINK to find total power consumed by the integral compressed air system for each random value of $\dot{m}$. The total power consumption values based on the random values of $\dot{m}$ and based on the variation of actual ambient temperatures from 8:00 am to 8:00 pm across all of 2021 were recorded. The total power consumption of the integrated compressed air system for each value of ($\dot{m}$) of air used in the simulation represents a total of the power required by the compressor to achieve operation, the power used by the cooling tower fan, and the power used by the cooling power pump. Figure 2 shows an example of total power consumed by the integral system on SIMULINK when a random value of 0.495 kg/s for airflow rate ($\dot{m}$) was utilized for a simulation from 8:00 a.m. to 8:00 p.m. throughout 2021. In the figure, the X-axis represents the normal workday hours of 8:00 a.m. to 8:00 p.m., while the Y-axis represents the total power consumed by the entire system in (kW), and each curve represents total hourly power consumption across all 12 months of 2021.

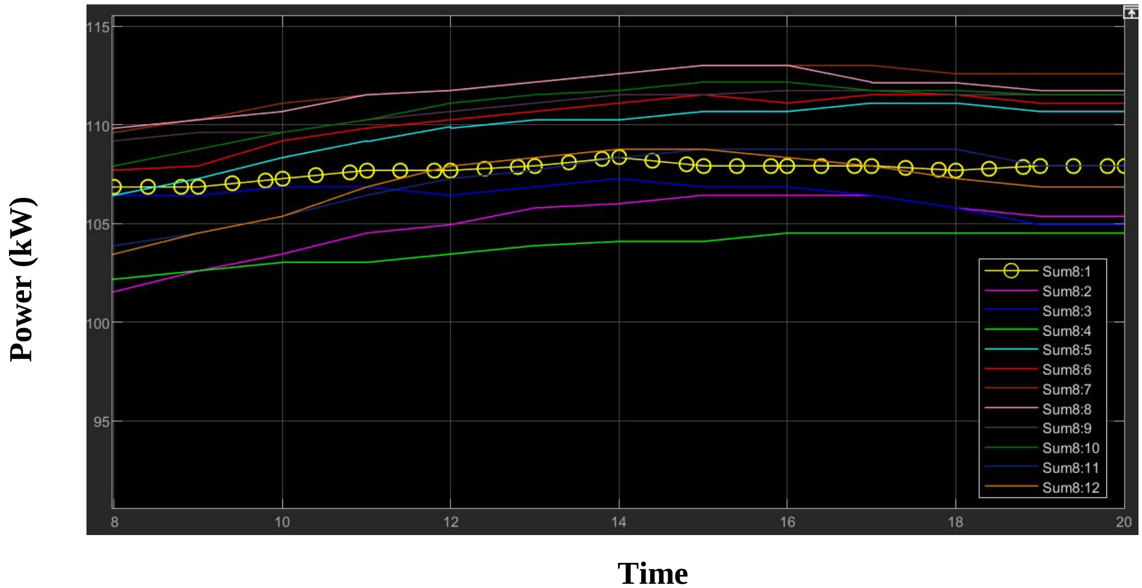


Figure 2: Total power consumption for the whole system for $\dot{m}$ = 0.495 kg/s on Simulink.

Curves values were imported after that by MATLAB to an Excel spreadsheet to calculate the summation value of the total power consumption of each hour across the year. The total power consumption for this simulation in 2021 was found to be 515,234.17 kWh/yr. The same operation was performed for the other 24 random values of the mass-flow rate of air to get a set of results for the integral system's total power consumption.

IV. SIMULATION RESULTS AND ANALYSIS

A set of results pertaining to total power consumption in the integral system, based on simulations of the 25 random values of the mass-flow rate of air were collected. An analysis was performed after that via Excel by generating a bell curve for these results, initially calculating the Mean value, Standard Deviation value, and then the Normal Z-Distribution values. The bell curve was generated based on the total power-consumption values per year (kWh/yr) for the results obtained from the simulation and the Normal Z-Distribution values for each result. Figure 3 below shows the aforementioned bell curve.

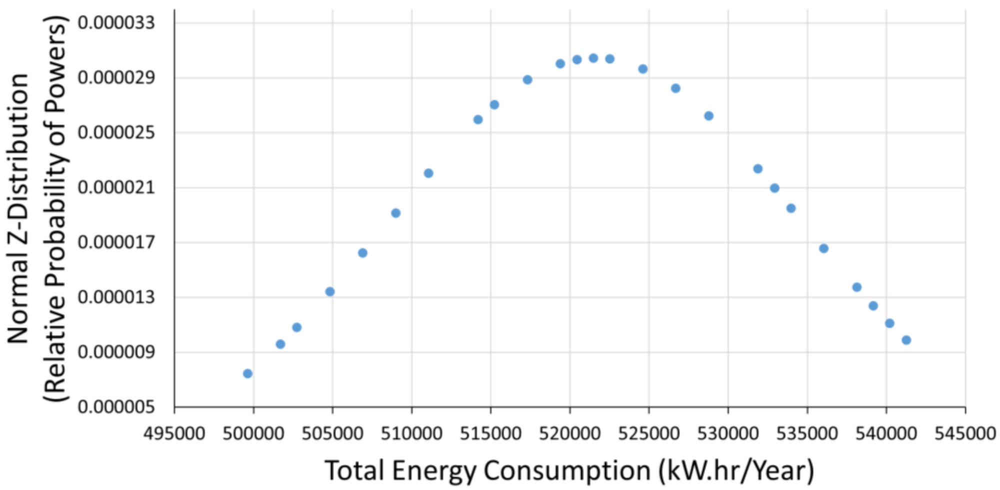
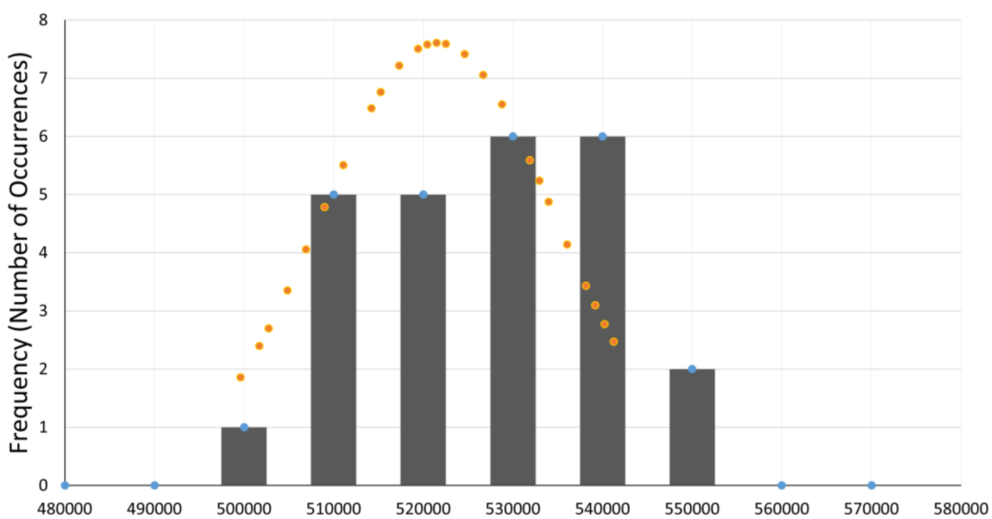


Figure 3: Bell curve for the simulations results.

It was found that the majority (68 percent) of the total power consumption values per year lie between 508,502 kWh/yr and 534,706 kWh/yr, 95 percent of the total power consumption values per year lie between 495,400 kWh/yr and 547,808 kWh/yr, and 99.7 percent of the total power consumption values per year lie between 482,298 kWh/yr and 560,910 kWh/yr. Figure 4 shows a histogram of the frequency of several total power consumption bins.



Total Power Consumption (KW·hr/Year)

Figure 4: Histogram of the frequencies of several total power consumption bins.

Based on the number of occurrences shown in Figure 4, it was found that among the performed 25 random simulations, the majority of total power consumption possibilities occurred two times in 530,000 kWh/yr and 540,000 kWh/yr, with 12 instances and a 48% possibility of occurrence; the total power consumption of 510,000 kWh/yr and 520,000 kWh/yr occurred 10 times, with a 40% possibility of occurrence; the total power consumption of 550,000 kWh/yr occurred 2 times, with an 8 percent possibility of occurrence; and the total power consumption of 500,000 kWh/yr occurred 1 time, with a 4% possibility of occurrence.

A. Additional Simulations and Analyses

In the previous section, authors used the parameter uncertainty for only one element of the system and simulated the whole year energy consumption of the system. In this section, the authors incorporated the effects of multiple elements uncertainties, but only simulated the instantaneous pick energy consumption. To do this, authors developed a MATLAB based simulation model and included the effects of more parameters uncertainty (outdoor temperature sensor tolerance, system operation temperature sensor tolerance, air and water flow capacity tolerances affecting the power consumption of the compressor, cooling tower fan and pump) in model when evaluating the energy consumption of the overall system. As it was noted earlier, this modeling is performed for the pick load condition instant only, but the intention here is to show not only the effects of different parameters uncertainty collectively, but to evaluate the effects of air leakage in the compressed air system on overall energy consumption of the system which is the main cause of energy loss in air compressed systems. The deterministic simulation is performed first in the MATLAB based simulation model (with no uncertainty considered) for the pick load condition with some specific inputs to the system. The results of this model showed the overall energy consumption of the system to be close to 111 kW. Another coding represented the simulation result (500 simulations) when the tolerances for the temperature sensors, and air and water flows are included in the model. The results as has been depicted in Figure 5 showed a possible total energy consumption range of 105 to 117 kW. The system energy consumption during the pick load, when there are 5% and 10% leaks in the system was performed as well. When there is 5% leak in the system, the overall energy consumption in pick instant, as it is shown in Figure 5, has a range of 111 to 123 kW. This represents a possibility of up to 12% energy loss (50% chance of 5.5% loss, and 25% chance of 7.5% loss) due to a 5% leak only. Finally, when there is a 10% air leak in the system, the overall energy consumption in pick instant has a range of 115.5 to 128 kW.

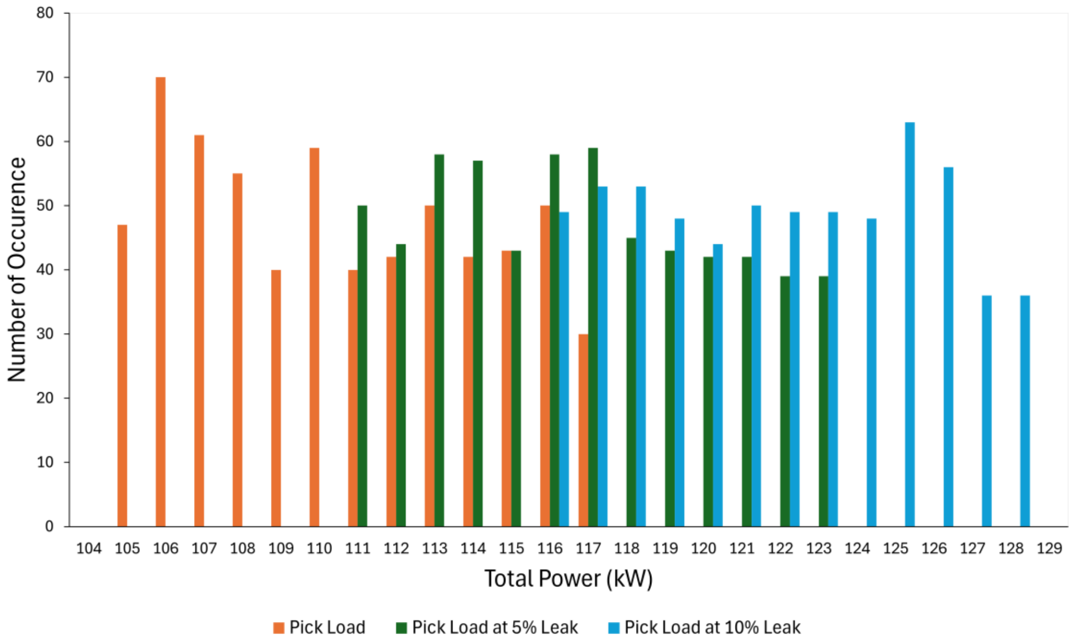


Figure 5: Histogram of the frequencies of total power consumption in 3 cases.

This, as it is shown in Figure 5, represents a possibility of up to 15% loss of energy due to a 10% leak (100% chance of 4% loss, 50% chance of 10% loss, and 31% chance of 12% loss).

V. CONCLUSION

A model for a compressed air system was prepared and then created on MATLAB Simulink. A set of simulations based on different random values within the allowable tolerance for a certain rated value of the mass-flow rate of air were run on Simulink for the created modeling. This rated value is 0.5 kg/sec, and the tolerance permitted for this value was found to be ± 4% (between 0.48 kg/sec and 0.52 kg/sec). It was found via simulation that the total power consumption in the compressed air system per year of the rated mass-flow rate of air (0.5 kg/sec) was 520,438 kWh/yr, but due to the allowable tolerance for the rated value of airflow into the compressor, we saw that the total consumption per the year can be any value between 499,621 kWh/yr and 541,256 kWh/yr. So, it was concluded that the total energy consumption of this compressor per year based on uncertainty in the air-flow rate to the compressor can vary across a remarkable range of 41,635 kWh/yr between 499,621 kWh/yr and 541,256 kWh/yr, instead of 520,438 kWh/yr. Also, modeling was done while multiple parameters uncertainty was considered. Simulation represented similar outcomes. In addition, the effects of air leaks were evaluated on overall energy consumption of the system, pointing to major energy losses due to 5 to 10% leaks only. Allowable tolerance in the mass-flow rate of the air used in air compressors can cause a considerable range of possible power consumption instead of only one calculated value, and that these tolerances are the source of uncertainty when predicting a compressed air system's total yearly energy consumption. To accurately predict total energy consumption, plant design and energy engineers designing any facility with air compressors should consider these tolerances in their calculations when predicting a compressed air system's total energy consumption, instead of depending only on one value for the mass-flow rate of air. In this paper, the authors proved - based on modeling and the simulation of a real compressed air system of a certain industrial process - that uncertainty has a remarkable effect on total energy consumption. They explained in detail a general method and provided a useful technique that can be employed for any compressed air system to predict the system's total energy consumption while also considering the uncertainty resultant from allowable tolerances in the air-flow rates. One important finding here is that a decrease in allowable manufacturing tolerances could contribute to reducing uncertainty and therefore rendering greater energy savings. Another important finding is that the authors have shown that only one unknown factor (e.g., equipment-test tolerance allowance) can contribute to 2.5% to 4% of uncertainty within a system's overall energy consumption. Given that guideline state that the allowable tolerances for airflow entering the compressor is 4% to 7% for different quantities of airflow, it can be seen that the uncertainty within the system's overall energy consumption can actually be even higher than the predicted 2.5% to 4% found here.

V. Future Work

The created compressed air modeling in this report can be implemented in many other research-based projects and experiences as well. The authors plan to use it in identifying other variables and changes that occur within integral compressed air systems and to study the effects of uncertainty resultant from these variables when predicting a compressed air system's energy consumption. The modeling can also be used to check the effects of the air leakages that take place when operating compressed air systems within industrial facilities. The produced air pressure used in this current research can also be modified within a specific range – say, to that of the operational ranges used in most facilities – to study how changing the inputs affects the outputs of compressed air systems. A lot of research ideas and expansion can be performed using this current model and based on the results of this research in the future, manufacturers and engineers at industrial facilities will be able to better increase their compressed air system's efficiency and performance, predict actual total energy consumption, and increase the system's energy efficiency. As noted earlier, the authors have evaluated the effects of uncertainty pertaining to the volumetric airflow quantity entering the air compressor on a typical compressed air system's overall energy consumption. The authors have shown that the permitted tolerances given by the regulatory standards based on manufacturers' testing structures can contribute to uncertainty when predicting the overall system's energy consumption. Of course, uncertainty can be generated from different (other) sources/equipment as well, and their inclusion would help us more accurately model energy consumption. As mentioned throughout the paper, the authors have only focused on only one uncertainty parameter (the quantity of compressed airflow) in developing this model. This model can be considerably improved by introducing the uncertainty parameter of other (more) equipment designated for usage in the overall plant. Such work would allow the user to perform a greater number of evaluations, such as sensitivity analysis, and point out which equipment is having the most profound impact on the plant's overall energy consumption.

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Dr. Javad Khazaii is an associate professor of mechanical engineering technology at Kennesaw State University (KSU). He has co-authored scientific articles and conference proceedings for the ASME and IBPSA. He is ranked 31st among academic scholars (lifetime) in the world in the field of "Heating, Ventilation, and Air Conditioning" by ScholarGPS in 2024.