Dynamic Simulation of Compressed Air Systems

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ABSTRACT

In recent years, energy engineers have examined industrial compressed air systems looking for opportunities to reduce the energy consumption, which in turn leads to operating cost savings. After identifying possible actions that might lead to a reduction in energy usage, it is necessary to perform an analysis to determine the projected energy and cost savings, and to estimate the cost of implementing the action. This analysis is a critical step in calculating the return on investment to determine if the recommended changes are cost effective. A number of sound recommendations are based on best practices and good engineering judgment. Often these methods employ approximate formulas and "rules of thumb", which produce reasonable results depending on the assumptions made. For compressed air systems that utilize multiple compressors and various control strategies, dynamic system simulation provides a method to investigate opportunities in energy reduction and system optimization.

In this paper, a dynamic compressed air system simulation model that was developed utilizing MATLAB/SIMULINK is presented. The model accounts for thermodynamic and fluid dynamic interactions within the compressed air system under a variety of operating conditions and control strategies. The system model is composed of component models that are linked to form the compressed air system. Each component model is based on relations that involve the key system variables. The component models discussed in this paper are two screw air compressors, an auxiliary air cooler, a receiver, the system piping and both regulated and unregulated air demand. The method of compressor control is load/unload.

The simulation program was utilized to investigate the effect of air pressure on the performance of the system. It is usual to recommend reducing the delivered pressure from the compressor as a way to reduce the compression work. However, when multiple compressors are used to serve a system with varying air demands, increasing the pressure settings and properly sequencing the compressors could result in a reduction of the system energy usage. Other factors that affect the optimal performance of the system include the volume of the compressed air storage tank (receiver), the temperature of the discharge air (affected by the capacity of the after cooler), and the temperature of the inlet air to the compressor. Because the simulation program bases the calculations on fundamental principles of thermodynamics and fluid dynamics, it accounts for the interaction of various system operating parameters on the systems performance. Two simulation studies are presented. Results from the simulation program are discussed and optimal operating parameters are discussed in light of the simulation results.

Introduction

One method for analyzing the overall energy efficiency of a compressed air system (CAS) is to examine the system from the supply side and the demand side. For instance, a large reduction in energy consumption can be obtained by reducing the demand for compressed air. This might be accomplished through a reduction in air leaks, eliminating compressed air used for blow offs, or utilizing electric motors in place of air actuators to perform the same operation. Energy efficiency improvements in supplying compressed air might be accomplished through the use of premium efficiency motors or more efficient compressor design. Another method of analysis is to consider the compressed air system as a whole. In this approach, improved energy efficiency can be addressed through examining the dynamics between supply and demand and the effects control strategies and operating conditions have on reducing the energy consumption. Dynamic system modeling is one tool that can be used for this analysis. Through computer simulation, various control strategies and system operating conditions can be examined to determine the optimum system configuration for a particular compressed air system.

In this paper a dynamic compressed air system simulation model that was developed utilizing MATLAB/SIMULINK is presented. The model accounts for thermodynamic and fluid dynamic interactions within the compressed air system under a variety of operating conditions and control strategies. The system model is composed of component models that are linked to form the compressed air system. Each component model is based on relations that involve the key system variables. The component models are two screw air compressors, an auxiliary air cooler, a receiver, the system piping and both regulated and unregulated air demand.

Compressed Air System Model

The software used to develop the CAS simulation was MATLAB/SIMULINK. Modeling with MATLAB/SIMULINK involves defining blocks, which have inputs and outputs and carry out specific functions. Usually a complex system is modeled by dividing it into component blocks (Cavallo, Setola & Vasca 1996) where each block represents a physical component of the CAS. In this work the system consisted of two screw compressors connected in parallel, an auxiliary air cooler, a receiver, the piping, and the pressure control system. Figure 1 illustrates the physical components considered for the CAS, while Figure 2 shows the SIMULINK diagram of the physical model.

In SIMULINK, each of the physical components is modeled using a block (refer to Figure 2). Each block is composed of several elemental blocks. Each block performs only a few operations. Each component block has inputs and outputs, which connect to other blocks to define the interactions between the components in the system. In some cases an input is a constant. As an example, the input "To1" is the inlet air temperature to Compressor 1. Data files can also serve as an input. The file "load.mat" contains time-varying volumetric airflow rate information which defines the Regulated Air Demand on the compressed air system due to pressure regulated devices. This file is explained in more detail below. Output signals can be written to external files for post-processing. In Figure 2, R1, R2 and R3 are "recorders" which are used to produce output data files from the simulation program. The output "Prec" (which goes into R3) is the pressure in the receiver tank. This output provides feedback to the system model for both the compressor controls and the "unregulated" air demand that results from air leaks and blow-off air usage.

Figure 1. Physical Model of the Compressed Air System

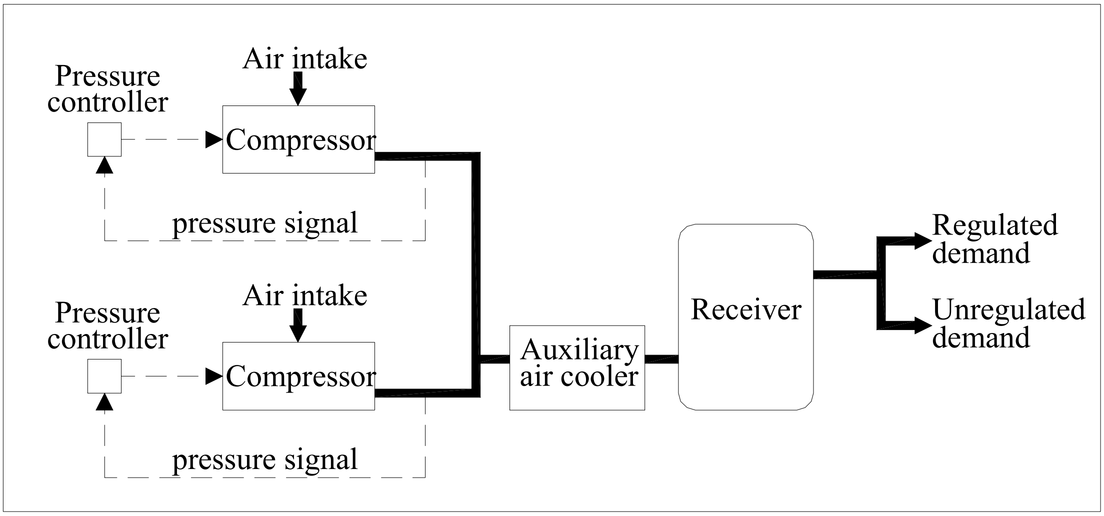
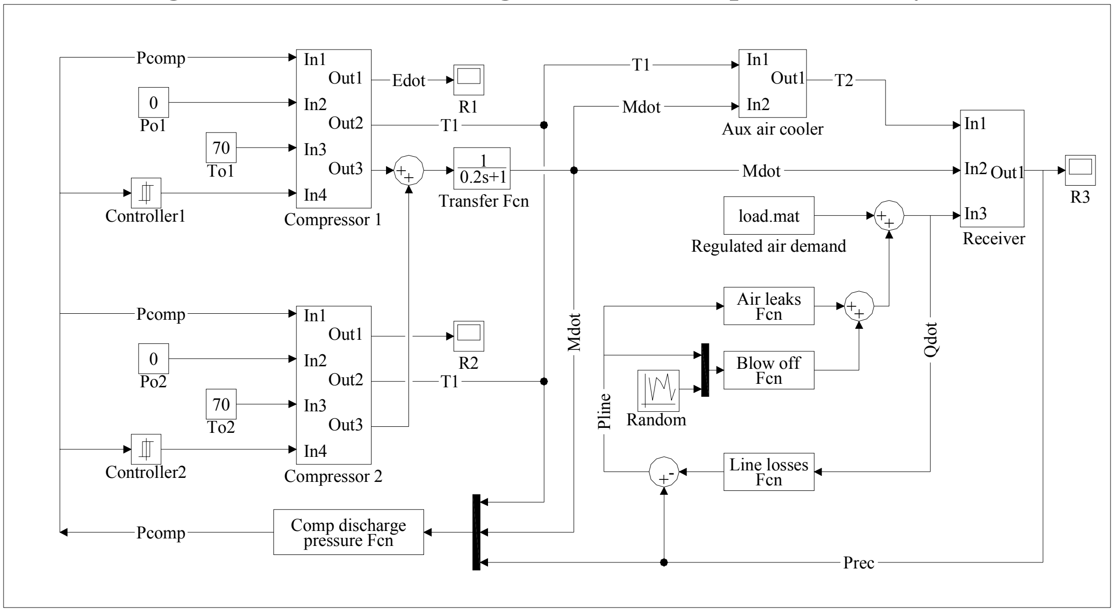


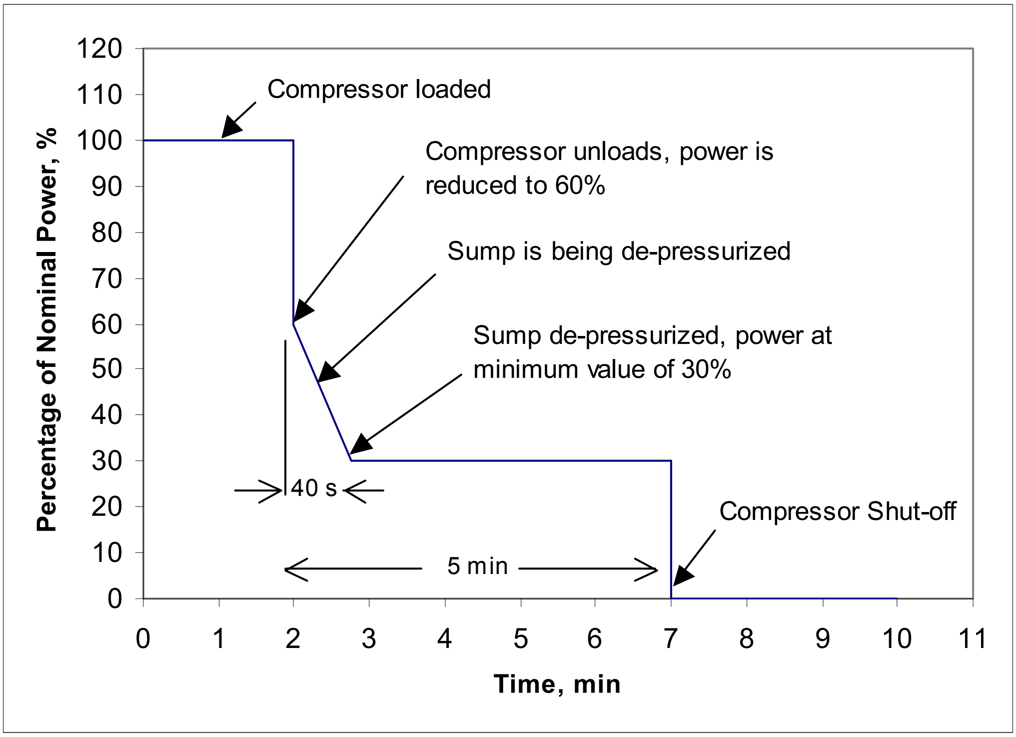
Figure 2. SIMULINK Diagram of the Compressed Air System.



In the present program, the output files created from running a simulation are post-processed in order to determine the annual electrical energy and electrical demand for the compressors. It is possible to include these calculations directly in the program, and this is something that will be incorporated in the future.

In many systems that utilize a flooded rotary screw compressor the oil sump tank is vented while the compressor is unloaded. After the compressor has been unloaded for a prescribed time, the compressor is shut off. In the present model, the assumption made is that when the compressor unloads, the power drops to 60% of the rated horsepower and the oil sump begins to de-pressurize. It is assumed that the power decreases linearly to a value of 30% of rated power during the 40 second de-pressurization process. If the compressor runs unloaded for a period of 5 minutes, the compressor is shut off. Figure 3 illustrates the compressor unloading sequence.

Figure 3. Compressor Unloading Sequence



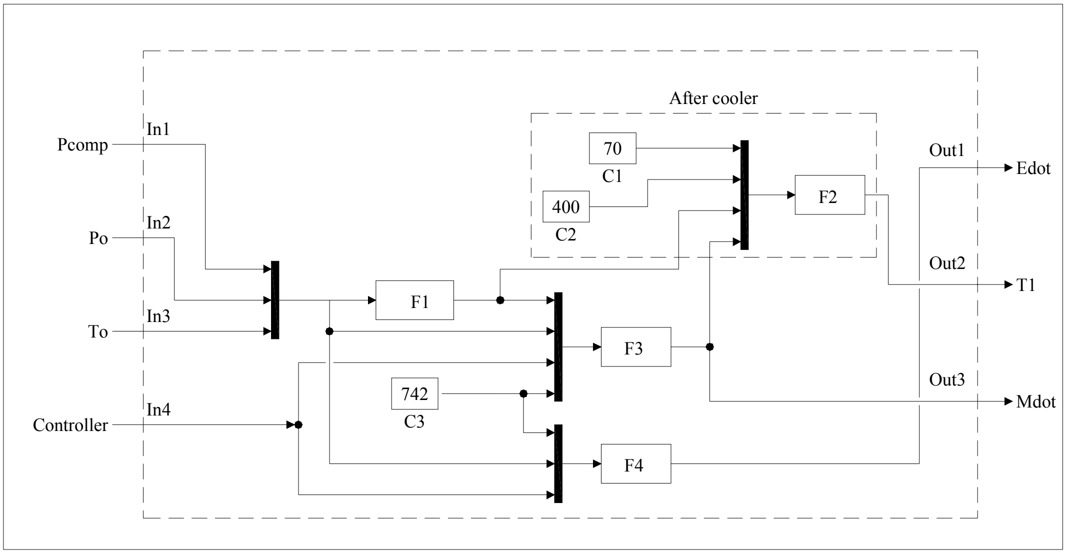
Compressor Model

The air compressor model was developed for an air-cooled, single-stage, flooded rotary-screw compressor. Figure 4 shows a SIMULINK diagram of the compressor model. The model consists of four inputs, three outputs and four functions. The inputs are the inlet air temperature (To, ^{o}F), the inlet air pressure (Po, psig), the discharge air pressure (Pcomp, psig) and the control signal (load/unload). The outputs are the electric power requirements of the compressor (Edot, kW), the discharge air temperature (T1, ^{o}F), and the air mass flow rate (Mdot, lb/min).

The four function blocks contain mathematical relations used to calculate an output. The function F1 is used to determine the air temperature leaving the compressor. The mathematical relationship used is found in the Compressed Air and Gas Handbook (Rollins 1989). The function F2 is used to calculate the temperature of the air leaving the after cooler. This calculation is based on the effectiveness-NTU method of heat exchanger analysis (Incropera & DeWitt 2002). The compressor's after-cooler was modeled as a cross-flow heat exchanger with both fluids unmixed. The function F3 is used to predict the air mass flow rate through the compressor. Performance data from a compressor manufacturer was used in a regression analysis to produce a piece-wise linear function relating mass flow rate to pressure. The function F4 is used to calculate the compressor power as a function of pressure.

Some of the functions in the air compressor model require additional parameters. For function F2, the room air temperature (C1, °F) and the size of the after cooler (C2, BTU/hr-°F) are required. Functions F3 and F4 require the nominal compressor output (C3, ft^3/min.)

Figure 4. SIMULINK Diagram for the Compressor



Receiver Tank Model

Figure 5 shows the SIMULINK block diagram of the receiver tank model. The fundamental equation governing the dynamics of the tank is the law of conservation of mass.

$$\frac{dm(t)}{dt} = m_i - m_o \qquad \text{[Eq. 1]}$$

where:

m_i = input mass flow rate
m_o = output mass flow rate
m(t) = total mass of air contained at time t,

The desired output from the receiver tank model is the air pressure at time t. By assuming ideal gas behavior and small changes in the air temperature, Equation 1 can be re-written as:

$$\frac{dP_{rec}}{dt} = \frac{(m_i - m_o) \cdot Rg \cdot T}{V_T} \qquad \text{[Eq. 2]}$$

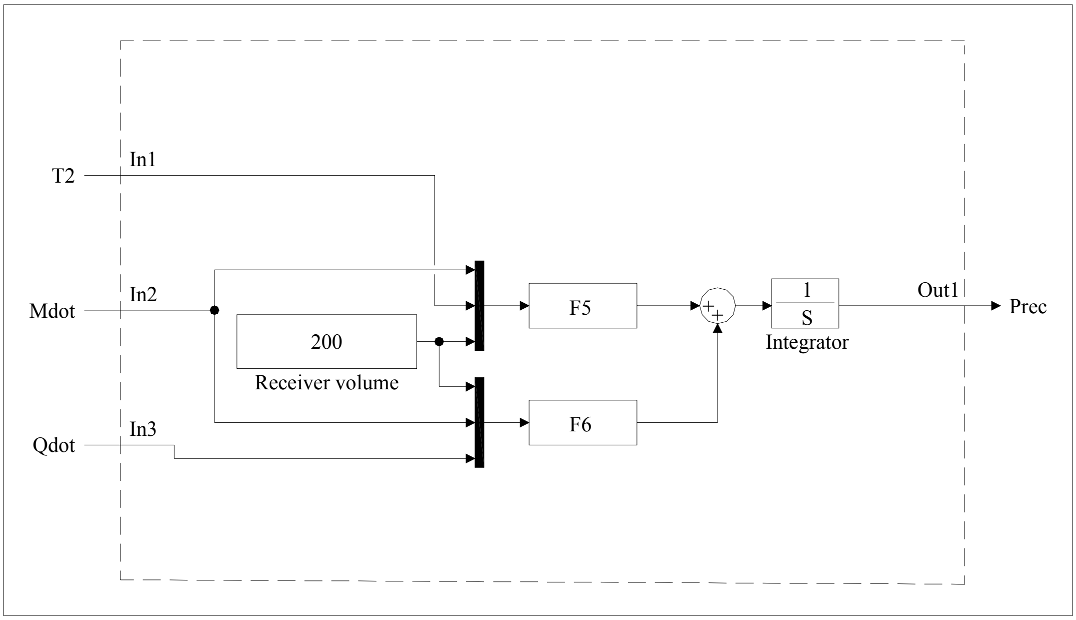
where:

P_{rec} = instantaneous air pressure in the tank
Rg = ideal gas constant for air
V_T = receiver tank volume
T = average temperature of the air in the tank

The functions contained in the gain blocks are the following:

F5(t) = gain related to air mass flow rate from the compressors.
F6(t) = gain related to the air demand flow rate.

Figure 5. SIMULINK Diagram for the Receiver Tank.



Auxiliary Air Cooler

The model for the auxiliary air cooler is similar to the after-cooler model found in the air compressor model shown in Figure 4. The purpose of the auxiliary air cooler is to further cool the air before it enters the receiver.

Time Delayed Mass Flow Rate from Compressor Inlet to Receiver Inlet.

There is a relatively small volume of air (compared to the volume of the receiver) in the system between the compressor and the inlet to the receiver that affects the airflow rate into the receiver tank. This volume is made up of piping, the oil sump, the after cooler and the auxiliary air cooler. When the compressor loads, there is some accumulation of air in this volume due to the compressibility of the air. This creates a time delay for the mass flow of air from the compressor into the receiver. In addition, there is a time delay that occurs between the time the compressor is given the command to load (or unload) and when the inlet valve responds. These combined effects were simulated using a first order transfer function block with a time constant of 2 seconds. This value was chosen arbitrarily. A better estimation for this value could be determined by observation of a real system. The function block is shown in Figure 2 as "Transfer Fcn."

Pressure Losses

While it is theoretically possible to model the pressure drop in a compressed air system in more detail (for both the piping network and the components), the approach taken in this model is to lump the piping and component pressure losses together. This was done by considering the pressure losses in the system as two groups. One group contains all the pressure loss from the compressor to the receiver tank while the second group contains all the pressure loss from the receiver tank to a certain point in the distribution system. This point would be where the air pressure is available for both regulated usage and un-regulated usage (air leaks and blow offs). For either group the relationship used to estimate the pressure loss is:

$$\Delta P = K \cdot Q^2 \qquad \text{[Eq. 3]}$$

where:

ΔP = pressure loss
K = resistance coefficient
Q = air flow rate

The value of K used in Equation 3 depends on which part of the system the pressure loss is being calculated. It's also important to note that the volumetric flow rate must be specified either in terms of actual volumetric airflow rate or standard volumetric airflow rate. Usually equipment requiring compressed air specifies the airflow rate in standard cfm, however, due pressure and temperature effects, the airflow rates in the system will be actual airflow rates. Both are used in the CAS model presented here. In Figure 2, the function blocks "Line losses Fcn" and "Comp discharge pressure Fcn" represent the two pressure loss groups.

Compressed Air Demand

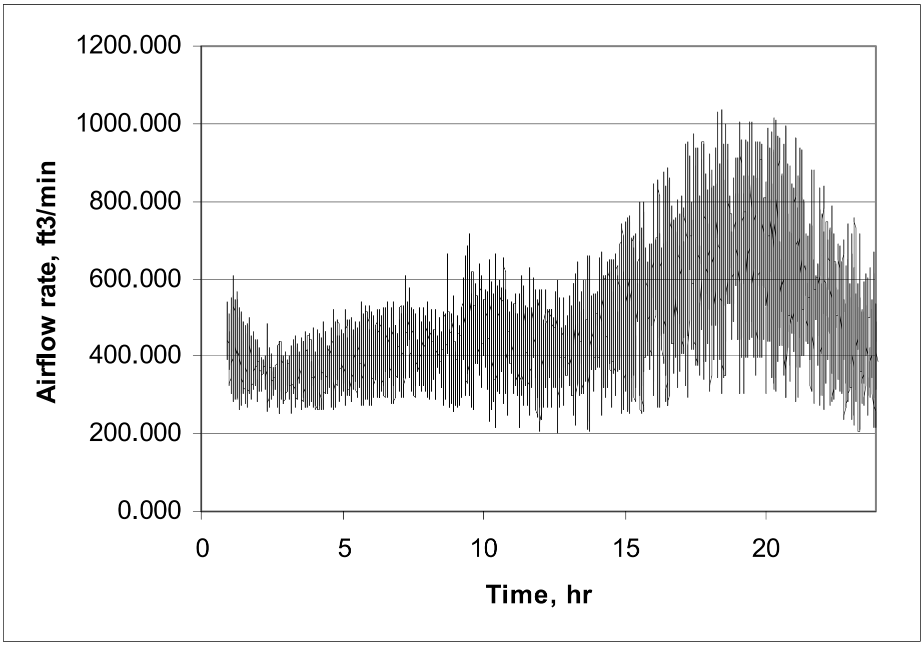
The total compressed air demand was modeled as coming from two components. The first component is the air usage that occurs downstream from pressure regulators. This is referred to as Regulated Air Demand. Regulated Air Demand is not affected by the system pressure as long as the pressure upstream of the regulators is maintained above a minimum level, and the pressure regulators function properly. The second component is the air usage that is affected by changes in the system pressure. This is referred to as Unregulated Air Demand and includes air leaks and all other uses (such as blow-offs) which are not controlled by a pressure regulator. The marginal variation of the unregulated demand with system pressure is known as the Artificial Demand.

As previously mentioned, one input to the CAS simulation model is a Regulated Air Demand (or load) data file. The data file represents the volumetric airflow rate needed (or demanded) by the pressure regulated portion of the system as a function of time. For any real CAS, the demand profile depends on several factors related to the equipment being served, system layout and equipment operating schedule. While an infinite number of demand profiles could be conceived, one was chosen and considered in this work. The profile contains 8,640 values of airflow rate values based on a 10-second time interval. The profile defines the Regulated Air Demand for a "typical" day.

The Regulated Air Demand profile is characterized for random occurrences of relative important temporary loads over a short period of time. The profile was shaped to account for what could represent a daily requirement for an industrial facility. The profile shows a first shift with low compressed air requirements, a second shift in which most of the plant's activity occurs, and finally a third shift with reduced compressed air requirements.

This profile is arbitrary and does not necessary reflect any particular plant's operation; however, based on actual measurements taken at manufacturing plants, the profile depicts realistic system loads. The regulated air demand load is shown in Figure 6.

Figure 6. Regulated Air Demand Profile



The Unregulated Air Demand was simulated by two groups: the air leaks and the blow-offs. In both cases, the relationship between pressure and volumetric flow rate, Q, is given by:

$$Q = C_v \cdot \sqrt{P_{rec} - \Delta P} \qquad \text{[Eq. 4]}$$

where:

C_v = flow coefficient
P_{rec} = pressure in the receiver tank
ΔP = pressure loss in the distribution piping as calculated using Eq.3

When calculating the Air Leaks component, it is assumed that C_v is a constant; however, Blow-offs occur at random times. Therefore, C_v must be modified to account for these pseudo-random occurrence. In Figure 2, the function block "Air leaks Fcn" is used to calculate air demand from air leaks, while the function block "Blow off Fcn" is used to calculate the air demand from blow offs. The use of the Random generator function as an additional input to the blow off function models the random use of blow-off air.

Pressure Controller

The pressure controller used in this work was a simple ON/OFF control. It works between two specified values of maximum pressure, P_{unload}, and minimum pressure, P_{load}. A relay block models the controller. The input to the relay block is the compressor discharge pressure, P_{comp}, if the discharge pressure reaches P_{unload}, then the block output is zero ("false") until the discharge pressure reaches P_{load}. When discharge pressure reaches P_{load}, the block output is then one ("true") until the discharge pressure reaches P_{unload}.

Simulation Studies

The SIMULINK compressed air system model was used for two simulation studies. The first examined the effect of the pressure settings of the compressors operating under cascade control on the energy consumption for the system. The second examined the size (volume) of the receiver tank on the energy consumption of the system. Each case is presented below.

Case 1: Effects of Varying the Pressure Control Settings for Cascading.

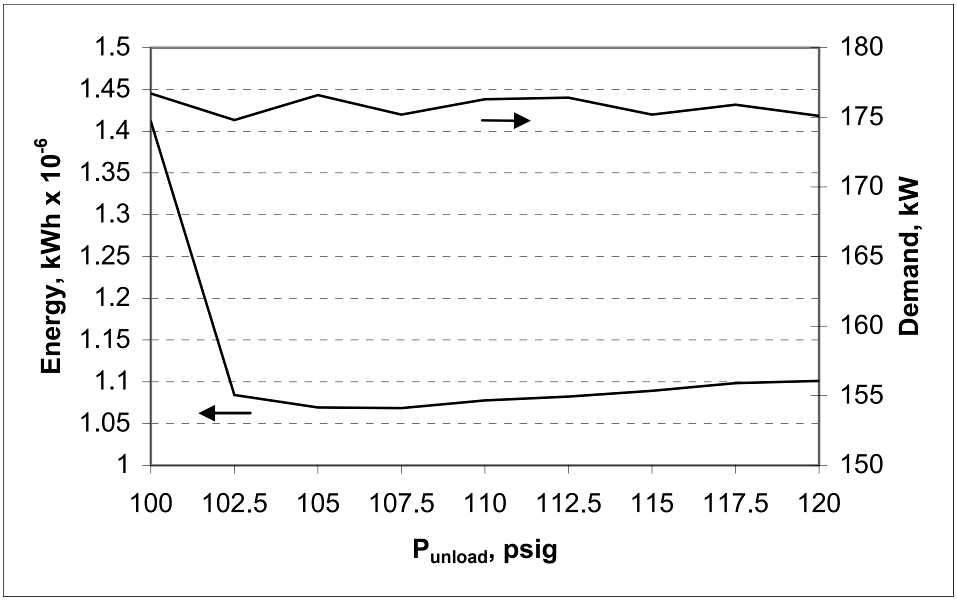
Cascading is a method of operating a multi-compressor system where additional compressors are started as the demand for air increases. Each compressor in the system has a different pressure set-point that tells the compressor to load. As system pressure falls due to increased airflow demand, a compressor will start compressing air when its "load" set-point pressure is reached. To prevent rapid load/unload operation of the compressor due to minor variations in system pressure, a 5 psig dead band is typically used. Thus the "load" set-point pressure is 5 psig less than the "unload" set-point pressure.

For this study, two 150-hp compressors were simulated using the Regulated Air Demand input file described before. The total air storage (receiver tank plus distribution piping) was considered to be 300 ft^3. The first compressor was used as the auxiliary source of compressed air by setting its set-point pressures, P_{load} and P_{unload}, to 95 psig and 100 psig, respectively. The second compressor, which acted as the lead compressor, used the same pressure dead band, but different values of the load and unload pressures. These values were varied for each simulation and the annual energy consumption and electrical demand were computed. The simulation was run for the following "unload" set-point pressures of the lead compressor: 100, 102.5, 105, 107.5, 110, 112.5, 115, 117.5, and 120 psig. A plot was created to show the electrical energy and electrical demand as a function of the lead compressor's "unload" pressure. The results are shown in Figure 7.

When operating air compressors in a cascade, the pressure settings play a significant role in the annual energy consumption and in the ability to maintain system pressure. As seen in Figure 7, the minimum annual energy usage is achieved when the lead compressor unload pressure is between 105 and 107.5 psig. Also, it can be observed that the energy usage increases rapidly when this unload pressure is reduced while it does not increase as rapidly when the unload pressure is increased. Based on this, a safe recommendation would be to operate the lead compressor with P_{unload} of 107.5 psig.

When considering the set-point pressures for the compressors, it is important to make sure the system pressure does not fall below a minimum value which would lead to operating problems for the compressed air equipment. On the other hand, if the set-point pressures are set too high, compressor energy will be wasted. The goal should be to determine the optimum pressure setting. By using the simulation model, the best pressure setting can be found that minimizes the energy usage while maintain acceptable system pressure.

Figure 7. Annual Energy Consumption and Electrical Demand versus P_{unload} of the Lead Compressor



Case 2: Effects of Varying the Size of the Receiver Tank

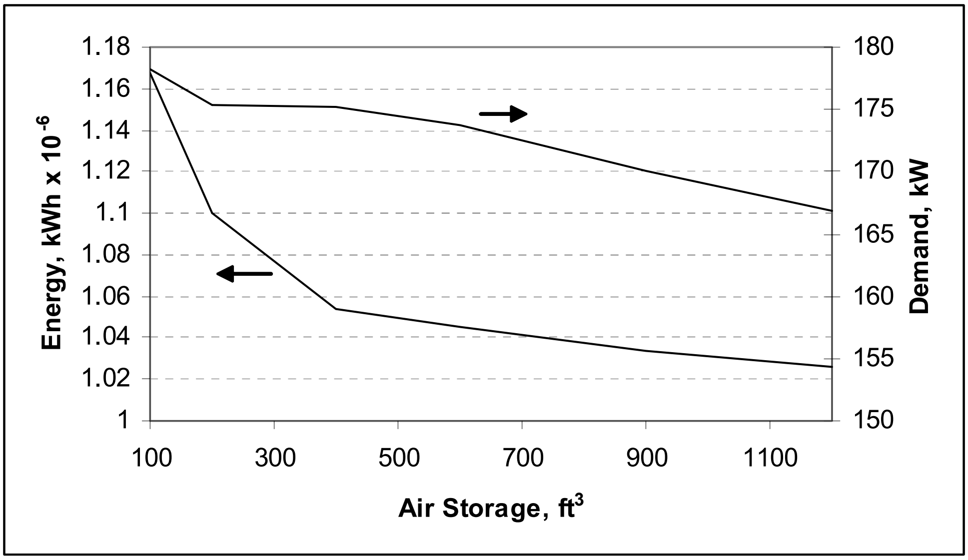
For this study, the size of the system receiver tank was considered. The values of the total air storage (receiver tank plus piping) used in the simulation were 100, 200, 300, 400, 600, 900, and 1200 ft^3. For each run, the estimated annual energy requirements and power demand were calculated and are shown in Figure 8.

Based on Figure 8, the size of the receiver tank (or the amount of total air storage) affects the annual energy usage of the system. The annual energy usage can be reduced as the storage volume is increased. There is a diminishing benefit to increasing the tank size as seen in the graph. An economic analysis based on electric utility rates could be used to determine whether or not added storage is cost effective.

Conclusions

Dynamic system modeling provides an analytical tool for evaluating compressed air system performance under a variety of operating conditions and control strategies. In this paper a specific CAS was examined in light of a typical regulated air demand profile and two cases were considered. For each case conclusions can be drawn; however, the reader should keep in mind that each case contains specific assumptions, which would vary from one compressed air system to another. The intent here is to present the usefulness of the modeling tool in evaluating CAS performance and to illustrate how the tool can be used to improve system performance.

Figure 8. Annual Energy Consumption and Electrical Demand versus Storage Capacity with Lead Compressor operated at P_{unload} of 105 psig



Future Model Development

While the present model only uses on/off control for the compressors, other control types are common in practice. These include modulating inlet valves and variable speed motors. In addition other feedback control schemes are common. These include proportional control and PID control. Furthermore, multiple compressor controls that include sequencing controls and network controls are used in practice. All of these and more can be modeled in SIMULINK, and could be incorporated in the future.

Addition refinements to the simulation would be to include a library of compressed air components such as filters (simulate clogging), localized reservoirs, and blocks that simulate air use by equipment such as printing machines, paper mills, plastic injection machines, etc. Coupled with blocks that represent the air distribution system, a detailed compressed air system model could be created.

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