CASE STUDY: EFFECT OF EXCESSIVE DUCT LEAKAGE IN A LARGE PHARMACEUTICAL PLANT

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ABSTRACT

A study of excessive air leakage in the ductwork of a large pharmaceutical plant located in the Southeast United States is executed in order to determine the energy loss associated with the excessive ductwork leakage. Much of the air supplied by the ductwork is delivered to clean rooms. The analysis requires the development of a model that is used to predict the increased energy costs. The model is applied for each 15 minute interval over the entire year (approximately 35,000 data points). The results are broken down into extra energy used to heat, humidify, and also cool/dehumidify the air over each 15 minute period throughout the year. The results are presented which show that the excessive duct leakage results in more than $1,000,000 loss over the life of the system. Also the additional makeup outside air dramatically increases the dust loading on the hepa filters used to clean the air before introduction into the clean rooms.

KEYWORDS
Duct Leakage, Energy Efficiency

INTRODUCTION

The situation being considered is an actual pharmaceutical manufacturing plant located in the Southeast United States. The HVAC duct work being investigated is used to supply clean rooms used in the manufacturing process. The duct work in question has approximately 3,800 square meters of surface area and air is delivered at a constant rate through the duct work. The installation of the duct work did not meet SMACCNA standards [1] in terms of leakage. For this ductwork the SMACCNA standard calls for a maximum leak rate of approximately 81.6 CMM. The duct work as installed had a leakage rate of 406.6 CMM. The excessive leak rate of 325 CMM requires that the plant's chillers and boilers provide additional chill water and steam to condition the outside air that must be supplied to replace the excessive leaked air from the system. In addition, the HEPA filters dust loading as well as fan HP is increased. This paper examines only the energy penalty associated with conditioning additional outside air due to leaks as compared to return air. The paper is divided into the following sections: (1) thermodynamic model, (2) results from application of model, and (3) conclusions.

1. THERMODYNAMIC MODEL

1.1 Introduction to Model

The air that leaks out of the duct system must be replaced with outside air rather than return air. For many hours/year, the energy level in outside air requires significantly more energy (either as heat or cooling) to reach project supply conditions. Thus, the excessive leak rate is considered to be a flow of outside air which must be conditioned to the return state.

1.2 Control of Temperature and Humidity

The following section describes the model used to determine whether heating or cooling and humidification is required. If the outside air humidity level is less than the desired value (in this case, .008291 kg water/air), the outside air is humidified to this level. Conversely, if the outside air humidity is higher than the required level, the outside air must be dehumidified to this level.

The "trigger" point between heating and cooling is 23 ^{o}C, i.e. if the outside air temperature is less than 23 ^{o}C, heating is required, and conversely, if the outside air is greater than 23 ^{o}C, cooling is required.

1.3 Governing Equations

The following equations, taken from reference [2] were employed in determining costs of heating and cooling of excessive leakage.

Relative humidity $\equiv \emptyset = P_v/Pg$ **[1]**

Where Pg is saturation pressure of water at air temperature and Pv is partial of water vapor in air all measured in bars

Specific humidity $\equiv \omega = .622\ [\ P_v/(\ .98- P_v)]$ **[2]**

Where Pv is measured in bars

Enthalpy per kg of dry air in kJ/kg = $h = T + \omega\ [2501.3 + 1.86T]$ [3]

Where T is dry bulb T in ^{o}C

$SensibleE_{total}$ = Energy required to heat or cool air in kJ/kg =
$Abs\ [h_{supply} - h_{outside}]$ **[4]**

Where h_{supply} = supply air enthalpy from Eq [3]
$h_{outside}$ = outside air enthalpy from Eq [3]

$LatentE_{total}$ = Latent energy required to humidify air in kJ/kg =
$568(\omega_{supply} - \omega_{outside})$ **[5]**

Where ω_{supply} = specific humidity of supply air
$\omega_{outside}$ = specific humidity of outside air

Annual Cost of Cooling = $(SensibleE_{total}\ /COP)(CMM_{excess})(Time)(\rho)(cost)$ **[6]**

Where E_{total} is given by Eq [4]
COP is the ratio of cooling energy achieved/input electrical energy
CMM_{excess} is the excess leak rate in cubic meters per minute
Time is the number of minutes of cooling over one year
ρ is the density of air in kg/cubic meter
cost is the cost of electricity in $/kJ

Annual cost of heating = $(SensibleE_{total}/\eta)(CMM_{excess})(Time)(\rho)(cost)$ **[7]**

Where E_{total} is given by Eq [4]

η is the efficiency of transforming natural gas energy to heating air
CMM_{excess} is the excess leak rate in cubic meters per minute
Time is the number of minutes of heating over one year
ρ is the density of air in kg/cubic meter
cost is the cost of natural gas in $/kJ

Annual cost of humidifying = ($LatentE_{total}$/η)(CMM_{excess})(Time)(ρ)(cost) **[8]**

Where $LatentE_{total}$ is given by Eq [5]

η is the efficiency of transforming natural gas energy to heating air
CMM_{excess} is the excess leak rate in cubic meters per minute
Time is the number of minutes of humidifying over one year
ρ is the density of air in kg/cubic meter
cost is the cost of natural gas in $/kJ

2. APPLICATION OF EQUATIONS

Weather data for the location of the plant were recorded for every fifteen minute interval for the year 2009. The properties recorded include termperature and relative humidity. The calculation of energy use is made for each fifteen minute interval based on these weather data.

Table 1 summarizes the sequence of steps used to calculate the energy used to condition outside air as opposed to return air on a KJ/Kg basis:

Table 1. Sequence to Calculate Energy Used to Condition Outside Air

Step	Action	Equation Employed
1	Use weather data for temperature T and relative humidity ω, to calculate partial pressure of water vapor in air, Pv	Eq[1]
2	Calculate the specific humidity of outside air using value of Pv from step 1	Eq [2]
3	Calculate the enthalpy of outside air using the temperature from weather data and specific humidity from step 2	Eq [3]
4	Calculate the return air enthalpy based on a temperature of 23 ^{o}C and sepcific humidity of .008291 kg water/kg dry air	Eq [3]
5	Calculate the heating or cooling required	Eq [4]
6	If the specific humidity of outside air is less than .008291 kg water/kg air, calculate the energy required to humidify air	Eq [5]
7	Calculate the annual cost of energy to cool excess leakage	Eq [6]
8	Calculate the annual cost of energy to heat excess leakage	Eq [7]
9	Calculate the annual cost of energy to humidify excess leakage	Eq [8]

CONCLUSIONS

The governing equations were applied according to the sequence listed in Table 1. Table 2 lists the results of this calculation based on 2009 weather data. In table 1, the average cost of electrical energy is assumed to be $.10/kwh and the cost of natural gas is assumed to average $10/million kJ. These average data are assumed to be for a 30 year life of the plant. In addition the boiler efficiency is assumed to be 80% in converting natural gas energy to steam and system losses in converting steam to heat the air are taken to be 5%. Hence, the true heating to fuel energy input rate, η, is 75%. Finally, the actual ratio of cooling to electrical energy input, COP, is considered to be 5 including all auxiliary inputs such as cooling tower fans and condenser water pumps.

Table 2. Summary Costs of Excessive Duct Leakage

Month	Amount of Energy to Cool Excess leakage in Kw-hr	Amount of Energy to Heat & Humidify Excess Leakage in millions of kJ	Cost of Energy to Cool Excess Leakage in $	Cost of Energy to Heat and Humidify Excess Leakage in $	Total Cost to condition Excess Leakage in $
January	1425	329.9231	28.5	4398.975	$ 4,427.48
February	4987.5	205.2855	99.75	2737.14	$ 2,836.89
March	1425	329.9231	28.5	4398.975	$ 4,427.48
April	24937.5	51.32138	498.75	684.285	$ 1,183.04
May	88350	6.28425	1767	83.79	$ 1,850.79
June	78375	5.236875	1567.5	69.825	$ 1,637.33
July	86925	4.1895	1738.5	55.86	$ 1,794.36
August	59850	20.9475	1197	279.3	$ 1,476.30
September	15675	163.3905	313.5	2178.54	$ 2,492.04
October	0	372.8655	0	4971.54	$ 4,971.54
November	0	594.909	0	7932.12	$ 7,932.12
December	0	703.836	0	9384.48	$ 9,384.48
Total	361237.5	2789.16	7224.75	37188.8	$ 44,413.55

The data shows that over a 30 year life the energy penalty associated with excessive duct leakage is more than 1.3 million dollars. The cost of the leakage far exceeds the marginal increase in the initial cost to install duct work that meets industrial standards. It should be pointed out that proper testing of the duct work installation before acceptance is critical because it usually is not cost effective to remedy leak problems after the plant is in operation. This is true in this particular case. The lack of initial proper testing has led to a situation where the leak rate penalty that exists must be accepted and the production plant is at a disadvantage in comparison to the equivalent plant with duct work with minimum leakage. Of course, the direct energy loss is only part of the loss due to excessive duct leakage. Poorer air quality leading to poorer quality of product, extra fan HP, and HEPA filter maintenance are further areas of economic loss.

REFERENCES

[1] No Author. 2010. *Architectural Sheet Metal Manual - SMACNA, 6th Edition*; Sheet Metal and Air Conditioning Contractor's National Association, Washington, DC.

[2] McQuiston, F.C., Parker, J.D., and Spither, J.D 2005. *Heating, Ventilating, and Air Conditioning, Sixth Edition*, John Wiley and Sons, New York.