SYSTEMATIC ENERGY AND EXERGY EFFICIENCY STUDY AND COMPARISON BETWEEN DIRECT FIRED AND INDIRECT FIRED HEATING SYSTEMS

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Bin Wang

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Ali Razban, Chair
Department of Mechanical and Energy Engineering
Dr. Jie Chen
Department of Mechanical and Energy Engineering
Dr. Eric Adams
Department of Mechanical and Energy Engineering

Approved by:

Dr. Jie Chen
Head of the Graduate Program

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SYMBOLS

c	specific heat, J/(kg K)
C	heat loss coefficient, W/K
E	energy, kJ
Ex	exergy, kJ
ex	specific exergy, kJ/kg
$\overline{ex}$	molar exergy, kJ/mol
h	specific enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/s
M	molar mass, kg/mol
$\dot{M}$	molar flow rate, mol/s
p	pressure, Pa
$\dot{q}$	volumetric flow rate, m^3/s
$\overline{R}$	molar gas constant, 8.314 J/(mol K)
s	specific entropy, kJ/(kg K)
T	temperature, K
V	volume, m^3
v	velocity, m/s
$\dot{W}$	work rate, kW
y	molar fraction, %
z	elevation, m
V	volume, m^3
η	energy efficiency
η	energy efficiency
ε	exergy efficiency

ρ	density, kg/m^3

ABBREVIATIONS

AFUE	annual fuel utilization efficiency
ACH	air change per hour
CFM	cubic feet per minute
HTHV	high temperature heating and ventilation
NG	natural gas
NHV	net heat value
PPM	parts per million

NOMENCLATURE

atm	atmosphere
com	combustion
ch	chemical
D	destruction
e	flow exiting the system
i	flow entering the system
j	heat transfer surface
o	dead state (outdoor air condition)
p	isobaric
sys	system
th	thermomechanical

ABSTRACT

Wang, Bin. M.S.M.E., Purdue University, August 2019. Systematic Energy and Exergy Efficiency Study and Comparison Between Direct Fired and Indirect Fired Heating Systems. Major Professor: Ali Razban.

The energy efficiency of space heaters is rated by Annual Fuel Utilization Efficiency (AFUE) governed by the Department of Energy in the United States which is a simple ratio of usable heat and fuel usage of a single heating device. It doesn't consider the overall performance of the heating system including not only the heating devices but also the characteristics of the building in different applications. The current AFUE method calculates only the energy efficiency which is thermodynamics first law efficiency. In this research, the systematic efficiency of a heating system rather than simple device efficiency has been defined and investigated. The systematic efficiency considers the overall efficiency of the whole heating system and it varies in the different applications even though with the same heating device. So it represents the performance of the system more precisely. Analytical models have been built to calculate both the systematic energy efficiency and exergy efficiency, and to evaluate the systematic energy and exergy efficiency of heating systems for direct fired and indirect fired heaters. Efficiency performances of the systems with these two types of heaters are compared. Sensitivities of input parameters for systematic energy efficiency are studied to show the impact towards systematic energy efficiency. Indoor carbon dioxide concentration level of direct fired heating system is also studied.

In a case study, results show that systematic energy efficiency of indirect fired heating system is always constant at heater device efficiency which is 80% while systematic energy efficiency of direct fired heating system varies from 40%-92% under different condition (heat loss coefficient, ambient temperature and air change requirement), indicating that simple device efficiency is not capable to evaluate the overall performance of heating system. New efficiency method such as systematic energy efficiency used in this research is needed to better describe the performance of the heating system. Results of indoor carbon dioxide level of direct fired heating system, from 1000 to 4500 PPM under different conditions, show that indoor air quality needs to be considered while using direct fired heating.

1. INTRODUCTION

Two types of heaters are commonly used for space heating purpose, indirect fired heaters and direct fired heaters. Combustion in an indirect fired heater is isolated from the indoor air stream while combustion in direct fired heaters happens within the supply air. For an indirect fired heating system, extra outdoor air beyond the building air change requirement is not needed because combustion doesn't affect the indoor air quality. For a direct fired heating system, combustion happens in the air stream which is supplied to the indoor space, so extra outdoor fresh air is required for safety purpose. Normally 100% fresh air is supplied to the heating space when using direct fired heaters.

A space heater's efficiency is measured by annual fuel utilization efficiency (AFUE) [1]. Specifically, AFUE is the ratio of annual heat output of the furnace or boiler compared to the total annual fossil fuel energy consumed by a space heater. Direct fired heaters are generally recognized to have a higher AFUE compared to indirect fired heater [2]. This AFUE is often assumed to estimate projected operating costs and may be used by public utility companies as the basis to award incentive rebates for "energy efficiency" in warehouses and industrial buildings. There are two drawbacks when using AFUE. Firstly, it is a simple ratio of usable heat and fuel usage of a single heating device. It doesn't consider the overall performance of the heating system including not only the heating devices but also the heating space characteristics according to different applications. For different type of space heaters, there are different requirements. For instance, indirect fired heaters where the combustion system and indoor air flow are separated, normally use 100% return air. Direct fired heaters which force the air directly through the flame to heat the space must use 100% fresh air in a space heating system in order to prevent waste combustion gas from accumulating inside a building. As a result, in a direct fired heating system, the heating requirement is increased due to outside air intake for heaters, which means extra energy is used to heat up the fresh air. By using AFUE, the extra amount of heat used to heat up the outside air cant be shown and understood. The other drawback of AFUE is that the energy efficiency is a First Law of Thermodynamics efficiency that is only based on conservation of energy [3], however, it doesn't consider the degradation of energy quality that takes place when high-quality energy resources, such as fossil fuels, are used to satisfy low quality thermal demands such as heating requirements. Another method needs to be applied to evaluate the overall heating system efficiency.

Energy is used everywhere in human activities. Economic criteria based on energy use are used in optimizing design and operation of different systems. However, ecological criterion, based on the concept of exergy, should be included as exergy represents a long term and sustainable view in energy resource usage [4]. Research related to the ecological cost of systems, which were based on the concept of exergy were carried on in recent decades and it becomes a very crucial area in energy system design and optimization [5].

Exergy is derived based on the Second Law of Thermodynamics and measures the quality of energy. It describes the maximum amount of work that can be done from an energy flow as it comes to the equilibrium with the reference environment, also known as dead state [3, 6–8]. Unlike energy conservation, exergy is always consumed in an irreversible process which happens in any real process [9]. Exergy is used to describe not only the energy performance but also the impact to the environment.

For indirect fired heaters, combustion is totally isolated from supply air flow. 100% return air is used for the heater itself. The combustion wont affect the indoor air quality. For direct fired heaters, the combustion of natural gas happens within the supply air stream. Carbon dioxide generated from natural gas combustion will go into the space been heated. Carbon dioxide level is a very important air quality factor in buildings. A carbon dioxide balance model is used in this research to evaluate the carbon dioxide level in the space been heated by direct fired heaters.

2. GOALS AND OBJECTIVES

The goal of this research is to propose a new efficiency definition which can be better than single heater efficiency while evaluating the overall performance of the heating system and evaluate system performances of direct and indirect fired heating systems using proposed systematic energy efficiency. Also compare the exergy efficiency of two types of system.

Objectives of this research:

1. Define systematic energy efficiency to evaluate heating system performance instead of using simple heater efficiency (AFUE).
2. Define heating system performance indicators: systematic energy efficiency and exergy efficiency, as well as carbon dioxide concentrate level for direct fired heating system.
3. Locate parameters (ambient temperature, space air change requirement and building envelope heat loss coefficient) which will affect performance indicators.
4. Build methodologies to analyse system performance indicators.
5. Performance indicators study for given case. Analyze and conclude with calculated results. Studies include systematic energy efficiency, exergy efficiency and carbon dioxide concentration level.
6. Determine the sensitivity of input parameters towards systematic energy efficiency.

3. METHODOLOGY

In this chapter, the methodology used to create each model in this research is introduced.

3.1 Thermodynamics Model for Energy and Exergy Etudy

The general equations of mass, energy and exergy balances are applied to the steady state conditions to the system. It is assumed that changes in kinetic and potential energy are negligible, thus are not considered.

3.1.1 Energy Analysis

A method rather than AFUE, the systematic energy efficiency, needs to be created to better describe the system effectiveness. Energy model is used to create and calculate the systematic energy efficiency.

Energy Balance

Energy balance equation of a control volume can be expressed by equation 3.1 according to the first law of thermodynamics [10]:

$$\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W} + \sum_i \dot{m}_i(h_i + \frac{v_i^2}{2} + gz) - \sum_e \dot{m}_e(h_e + \frac{v_e^2}{2} + gz_e) \tag{3.1}$$

There is no boundary work done by or to the system as building envelope remains unchanged.

Systematic Energy Efficiency Definition

In a commercial or industrial space which needs to be heated, the inner space is always maintained at a higher temperature than outdoor environment. In the steady state, heat is continuously being lost through the boundary. Building standards, such as ASHRAE Standard 62.1 [11], require ventilation during periods when the building is occupied by people. The outside fresh air from the ventilation results in another kind of heat loss. Assuming there is no other heat source inside the building envelope, the total heat loss of the control volume can be considered as heating requirement or heating load. The systematic energy efficiency is defined by equation 3.2 and 3.3:

$$\eta_{SYS} = \frac{\textit{Heating Load}}{\textit{NG Consumption in term of W(Btu/h)}} \tag{3.2}$$

$$\begin{aligned} &\textit{Heating Load} \\ &\quad = \textit{Heat Loss Through Boundary} + \textit{Heat Loss Through Ventilation} \\ &\quad = \dot{Q}_{envelope} + \dot{Q}_{ventilation} \end{aligned} \tag{3.3}$$

The ventilation mentioned in this section refers to the original ventilation requirement of the building, its not related to heater air flow rate.

According to ASHRAE Standard 62.1, the fresh air flow required for a building is related to several parameters including zone area and maximum zone population [11]. When the zone population is very low (no people or few people working in this space such as warehouse), the required ventilation could be low. Sometimes the direct fired heater will bring in more fresh air than that is needed to satisfy the requirement for ventilation. The portion of the fresh air above the ventilation air change requirement is considered unnecessary and will result in more energy consumption.

Systematic Energy Efficiency Calculation

Direct Fired Heating System

The following equations can be used to calculate the systematic energy efficiency for direct fired heating system.

For a certain building which needs heating, the heat loss through the building envelope can be calculated as [12]:

$$\begin{aligned}\dot{Q}_{envelope} &= (U_{walls} \times A_{walls} + U_{roof} \times A_{roof}) \times (T_{in} - T_{out}) \\ &= C \times (T_{in} - T_{out})\end{aligned} \tag{3.4}$$

Where,

U_{walls} is the overall thermal transmittance of walls, $W/(m^2K)$ $(Btu/(ft^2h\text{°F}))$,

U_{roof} is the overall thermal transmittance of roof, $W/(m^2K)$ $(Btu/(ft^2h\text{°F}))$,

A_{walls} is the area of walls, m^2 (ft^2),

A_{roof} is the area of roof, m^2 (ft^2),

T_{in} is the indoor temperature, °C (°F),

T_{out} is the outdoor temperature, °C (°F),

C is the heat loss coefficient of the building and its constant for a certain building, W/K $(Btu/(h\text{ °F}))$.

The heat loss through ventilation can be calculated as [13, 14]:

$$\dot{Q}_{ventilation} = c_p \times \dot{m}_{ventilation} \times (T_{in} - T_{out}) \tag{3.5}$$

$$\dot{m}_{ventilation} = ACH \times \frac{V \times \rho}{3600} \tag{3.6}$$

Where,

c_p is the isobaric specific heat of air, $J/(kgK)$ $(Btu/(lbm\text{°F}))$,

$\dot{m}_{ventilation}$ is the mass flow rate of required air change, kg/s (lbm/s),

ACH is the required air change per hour,

V is the volume of the building space, m^3 (ft^3),

ρ is the air density, kg/m^3 (lbm/ft^3).

The energy input rate from a heater can be calculated as [13]:

$$\dot{Q}_{input} = c_p \times \dot{m}_{heater} \times (T_{supply} - T_{out}) \tag{3.7}$$

Where,

$\dot{m}_{heater}$ is the air mass flow rate of heater, kg/s (lbm/s),

T_{supply} is the supply air temperature of the heater, °C (°F),

According to energy balance in this system, $\dot{Q}_{input}$ should be equal to actual heat loss rate if $\dot{m}_{heater}$ is the same as $\dot{m}_{ventilation}$.

$$\begin{aligned} \dot{Q}_{input} &= Actual\ Heat\ Loss\ Rate \\ c_p \times \dot{m}_{heater} \times (T_{supply} - T_{out}) &= \dot{Q}_{envelope} + \dot{Q}_{ventilation} \end{aligned} \tag{3.8}$$

$$\begin{gathered} c_p \times \dot{m}_{heater} \times (T_{supply} - T_{out}) = \\ C \times (T_{in} - T_{out}) + c_p \times \dot{m}_{ventilation} \times (T_{in} - T_{out}) \end{gathered} \tag{3.9}$$

Here, $\dot{m}_{heater}$ equals to $\dot{m}_{ventilation}$. Then we can calculate $\dot{m}_{heater}$.

$$\dot{m}_{heater} = \frac{C \times (T_{in} - T_{out})}{c_p \times (T_{supply} - T_{in})} \tag{3.10}$$

In different scenario, $\dot{m}_{ventilation}$ could be different. When the given $\dot{m}_{ventilation}$ is lower than the value we calculated in the previous procedure, it means the heater provides more fresh air than what is required. Please notice that we dont need to recalculated $\dot{m}_{heater}$ in this case because $\dot{m}_{heater}$ is the actual fresh air mass flow rate for the system. So use equation 3.11 to calculate the systematic energy efficiency [10]:

$$\begin{aligned} \eta_{SYS} &= \frac{Heating\ Load}{\dot{Q}_{input}/\eta_{heater}} \\ &= \frac{\dot{Q}_{envelope} + c_p \times \dot{m}_{ventilation} \times (T_{in} - T_{out})}{c_p \times \dot{m}_{heater} \times (T_{supply} - T_{out})/\eta_{heater}} \\ &= \frac{C \times (T_{in} - T_{out}) + c_p \times ACH \times \frac{V \times \rho}{3600} \times (T_{in} - T_{out})}{c_p \times \frac{C \times (T_{in} - T_{out})}{c_p \times (T_{supply} - T_{in})} \times (T_{supply} - T_{out})/\eta_{heater}} \\ &= \frac{(C + c_p \times ACH \times \frac{V \times \rho}{3600}) \times (T_{supply} - T_{in}) \times \eta_{heater}}{C \times (T_{supply} - T_{out})} \end{aligned} \tag{3.11}$$

Where,

η_{heater} is the heater device efficiency.

When the given $\dot{m}_{ventilation}$ is higher than the value we calculated in the previous procedure, it means the heater provides less fresh air than what is required. So use equation 3.12 to recalculate the $\dot{m}_{heater}$:

$$\begin{aligned} c_p \times \dot{m}_{heater} \times (T_{supply} - T_{out}) \\ = \dot{Q}_{envelope} + c_p \times \dot{m}_{ventilation} \times (T_{in} - T_{out}) \end{aligned} \tag{3.12}$$

Then the systematic energy efficiency will be:

$$\begin{aligned} \eta_{SYS} &= \frac{Heating\ Load}{\dot{Q}_{input}/\eta_{heater}} \\ &= \frac{\dot{Q}_{envelope} + c_p \times \dot{m}_{ventilation} \times (T_{in} - T_{out})}{c_p \times \dot{m}_{heater} \times (T_{supply} - T_{out})/\eta_{heater}} \\ &= \eta_{heater} \end{aligned} \tag{3.13}$$

It means when the required air change flow rate is beyond the air flow rate of the direct fired heater, the systematic energy efficiency will be the same as the heater device efficiency.

From the calculation we know that if air change requirement is lower than air flow rate of direct fired heater, the systematic energy efficiency is a function of air change requirement, ambient temperature and supply air temperature of the direct fired heater for a certain building (constant envelope heat loss coefficient, volume and indoor air temperature). If the air change requirement is higher than air flow rate of direct fired heater, systematic energy efficiency will be equal to heater device efficiency.

Indirect Fired Heating System

For indirect fired heating system, according to energy balance, heat input rate should be equal to heat loss rate.

$$\dot{Q}_{input} = \dot{Q}_{envelope} + \dot{Q}_{ventilation} \tag{3.14}$$

Systematic energy efficiency of indirect fired heater can be calculated as:

$$\begin{aligned}\eta_{SYS} &= \frac{Heating\ Load}{\dot{Q}_{input}/\eta_{heater}} \\ &= \frac{\dot{Q}_{envelope} + \dot{Q}_{ventilation}}{(\dot{Q}_{envelope} + \dot{Q}_{ventilation})/\eta_{heater}} \\ &= \eta_{heater}\end{aligned} \tag{3.15}$$

So under any condition, systematic energy efficiency of indirect fired heating system is always constant at the heater device efficiency.

3.1.2 Exergy Analysis

Exergy can be divided into the physical exergy and chemical exergy. Exergy is a property which defines the maximum useful work that could be done from a system at specified state. The work potential of the system tends to be measured in a given environment state (also known as dead state). For a space heating system, its better to set the dead state at the outdoor air state because heat in this system will eventually be transferred to the ambient. So the temperature of the dead state is the same as outdoor air temperature (T_o), and the pressure of the dead state is assumed to remain at 100 kPa (p_o).

Exergy Balance

The general exergy balance applied to a control volume is expressed by equation 3.16 [10]:

$$\begin{aligned}\frac{dEx_{CV}}{dt} = &\sum_j (1 - \frac{T_o}{T_j})\dot{Q}_j - (\dot{W}_{CV} - \dot{p}_o\frac{dV_{CV}}{dt}) \\ &+ \sum_i \dot{m}_i ex_i - \sum_e \dot{m}_e ex_e - \dot{E}x_D\end{aligned} \tag{3.16}$$

Exergy Calculation

The specific exergy of a flow can be split into chemical exergy and thermomechanical exergy (also known as physical exergy).

$$ex = ex^{ch} + ex^{tm} \tag{3.17}$$

The thermomechanical exergy represents the deviation in temperature and pressure between the flowing matter and the local environment. It also includes the kinetic and potential energy, although they are negligible in this study. The chemical exergy represents the deviation in chemical composition between the flowing matter and the local environment.

The thermomechanical exergy can be expressed as:

$$ex^{tm} = h - h_o - T_o(s - s_o) \tag{3.18}$$

Where h is the specific enthalpy of the flowing matter, s is the specific entropy of the flowing matter, while $h_o = h(T_o, p_o)$ and $s_o = s(T_o, p_o)$.

The molar chemical exergy can be expressed as:

$$\overline{ex}^{ch} = \sum_i y_i \overline{ex}_i^{ch,o} + \overline{R}T_o \sum_i y_i ln(y_i) \tag{3.19}$$

Where $\overline{ex}_i^{ch,o}$ is the standard chemical exergy [15, 16]; y_i is the molar fraction of each species. The standard chemical exergy can be found in source [17].

The specific chemical exergy can be calculated by equation 3.20,

$$ex^{ch} = \frac{\overline{ex}^{ch}}{M} \tag{3.20}$$

Where M is the molar mass of flow.

To calculate chemical exergy of NG flow and air flow, molar fraction of each component is required. NG and air components are listed in Table 3.1 [18].

Table 3.1.
Components of NG and air.

NG Components	mol %	Air Components	mol %
Methane (CH_4)	94.9	Nitrogen (N_2)	78.08
Ethane (C_2H_6)	2.5	Oxygen (O_2)	20.95
Propane (C_3H_8)	0.2	Argon (Ar)	0.934
Butane (C_4H_{10})	0.06	Carbon Dioxide (CO_2)	0.035
Pentane (C_5H_{12})	0.02		
Hexanes plus	0.01		
Nitrogen (N_2)	1.6		
Carbon Dioxide (CO_2)	0.7		
Oxygen (O_2)	0.02		

Exergy Efficiency

In exergy balance equation, the system is assumed to be at steady status. There is no boundary work done by/to the system. It is also assumed that there is no electrical work done by/to the system. So the equation 3.16 can be simplified to equation 3.21:

$$\sum_i \dot{m}_i ex_i = -\sum_j (1 - \frac{T_o}{T_j})\dot{Q}_j + \sum_e \dot{m}_e ex_e + \dot{E}x_D \tag{3.21}$$

Exergy efficiency is defined as equation 3.22 [19]:

$$\varepsilon = \frac{Ex_{out}}{Ex_{in}} = \frac{\sum_e \dot{m}_e ex_e}{\sum_i \dot{m}_i ex_i} \tag{3.22}$$

3.2 Carbon Dioxide Level Study

For direct fired heaters, the combustion of natural gas happens within the supply air stream. Carbon dioxide generated from natural gas combustion will go into the space been heated. Carbon dioxide level is a very important air quality factor in buildings. A carbon dioxide balance method is introduced in section 2.2.1 to evaluate the carbon dioxide level in the space using direct fired heater.

The concentration of carbon dioxide in a space will finally reach a balance point at which it keeps steady. In this research, only final steady carbon dioxide concentration level is considered. This level of concentration is what needs to be evaluated. In order to study the impact of a direct fired heater on indoor air quality, the carbon dioxide generated by human and other process inside the building is not considered.

3.2.1 Carbon Dioxide Balance

Parts per Million (PPM) is normally used to indicate the carbon dioxide concentration. PPM is defined here as the volumetric percentage [20]. At 1atm pressure, we can assume the air is ideal gas. For an ideal gas, the molecular percentage is equal to the volume percentage. The carbon dioxide molecular percentage in the atmosphere

Table 3.2.
Components of NG and net heat value.

NG Components	mol %	NHV (kJ/kg)	NHV (Btu/lb)
Methane (CH_4)	95	49,853	21,433
Ethane (C_2H_6)	3	47,206	20,295
Nitrogen (N_2)	2	0	0

is very low (0.04%), as a result, the change of carbon dioxide PPM has very limited impact on the density of the air. So, we will assume that carbon dioxide PPM change of air wont affect air density.

We assume the natural gas consists of 95% of CH_4, 3% of C_2H_6 and 2% of N_2 by mole, ignoring other compounds since other components in natural gas are very small [18]. Table 3.2 shows the component molecular percentage and net heat value (NHV), also known as lower heating value [21] of each component. We will assume N_2 wont participate in combustion, so there is no heat value of N_2 given.

The molar mass of natural gas can be calculated by equation 3.23,

$$M_{NG} = 95\% M_{CH_4} + 3\% M_{C_2H_6} + 2\% M_{N_2} = 0.01666\, kg/mol \tag{3.23}$$

Where, M_{NG} is molar mass of natural gas,

M_{CH_4} is molar mass of CH4, 0.016 kg/mol,

$M_{C_2H_6}$ is molar mass of C2H6, 0.030 kg/mol,

M_{N_2} is molar mass of N2, 0.028 kg/mol,

The net heat value of natural gas can be calculated by equation 3.24,

$$NHV_{NG} = \frac{95\% M_{CH_4} NHV_{CH_4} + 3\% M_{C_2H_6} NHV_{C_2H_6}}{M_{NG}} = 48,034\, kJ/kg \tag{3.24}$$

It is assumed that natural gas combustion is complete, so the carbon dioxide molar flow rate increased by natural gas combustion can be calculated by equation 3.25,

$$\dot{M}_{com} = \frac{Natural\ Gas\ Input}{NHV_{NG}M_{NG}}(95\% \times 1 + 3\% \times 2) \tag{3.25}$$

Where,

$\dot{M}_{com}$ is the carbon dioxide molar flow rate increased by natural gas combustion.

The unit of natural gas input here is kJ/s.

The carbon dioxide concentration balance in a steady system can be presented by equation 3.26,

$$\frac{\dot{m}_s PPM_{atm}}{M_{air}} + \frac{\dot{m}_{AC} PPM_{atm}}{M_{air}} + \dot{M}_{com} = \frac{\dot{m}_{exf} PPM}{M_{air}} \tag{3.26}$$

Where,

$\dot{m}_s$ is mass flow rate of supply fresh air by heater,

$\dot{m}_s$ is mass flow rate of addition air change beside fresh air supply by heater,

$\dot{m}_{exf}$ is mass flow rate of air exfiltration in the space,

$\dot{M}_{com}$ is the carbon dioxide molar flow rate increased by natural gas combustion,

PPM_{atm} is the carbon dioxide PPM of the atmosphere,

PPM is carbon dioxide PPM of the space.

According to mass balance in a steady flow:

$$\dot{m}_s + \dot{m}_{AC} + \frac{Natural\ Gas\ Input}{NHV_{NG}} = \dot{m}_{exf} \tag{3.27}$$

Here, natural gas input is term of Btu/h and can be transferred to kW, divided by NHV of natural gas in term of kJ/kg, we can get the mass flow rate of natural gas supplied to the system in term of kg/s.

Based on equation 3.26 and 3.27, we calculate the carbon dioxide concentration in the space in PPM.

3.3 Sensitivity Analysis

Several input parameters will impact the systematic energy efficiency. Sensitivity study is necessary to evaluate how the different input parameters will affect the output (systematic energy efficiency).

Sensitivity analysis is used to determine how the independent variable values will impact a particular dependent variable under a given set of assumptions. It is also known as the what-if analysis. Sensitivity analysis helps in analyzing how sensitive the output is by changing one input while keeping the other inputs constant [22].

3.3.1 Measurement of Sensitivity Analysis

Following steps are used to conduct sensitivity analysis [22]:

1. First, the base needs to be defined. A set of inputs are determined, and the output based on the inputs needs to be calculated.

2. Then recalculate the value of the output with a new value of each input while keeping other inputs constant.

3. Find the percentage change in the output and the percentage change in the input.

4. The sensitivity is calculated by dividing the percentage change in output by the percentage change in input, shown in equation 3.28.

$$Sensitivity = \frac{(Output_1 - Output_0)/Output_0}{(Input_1 - Input_0)/Input_0} \tag{3.28}$$

Where,

$Input_0$ is the input parameter of baseline,

$Input_1$ is the new input parameter,

$Output_0$ is the output of baseline (calculated based on $Input_0$,

$Output_1$ is the output calculated based on $Input_1$.

The conclusion would be that the higher the sensitivity of a certain input is, the more sensitive the output is to that input and vice versa.

4. SYSTEM MODELS

Models created and used in this research include systematic energy and exergy models, carbon dioxide concentration model and sensitivity model. The methodology used in there models are introduced in chapter 3.

4.1 Systematic Energy and Exergy Modelling

Simulink is used to simulate the indirect and direct fired heating system based on thermodynamics models. The schematic diagrams of an indirect fired and direct fired heating system are shown in Figure 4.1 and Figure 4.2, respectively. The control volume boundary of the systems is set outside the building envelope to make the surface temperature of boundary the same as the ambient temperature, so that the exergy transfer through boundary can be counted as exergy loss (or exergy destruction) according to exergy balance equation 3.9. In an indirect fired heating system, the space is considered to be at atmospheric pressure. Infiltration should be considered for this type of system due to the wind flow [23]. In direct fired heating system, the space is at positive pressure (slightly higher than atmosphere pressure) because direct fired heater brings in fresh air as heating supply. Exfiltration takes place due to the pressure difference and can also take place based on ventilation system operation.

4.2 Carbon Dioxide Concentration Level Modelling

The carbon dioxide concentration level model is created based on the methodology in section 3.2. Only steady status is considered, so a simple calculation model is needed. It can be calculated based on Excel. The average carbon dioxide concentration in the atmosphere is 413 PPM [24].

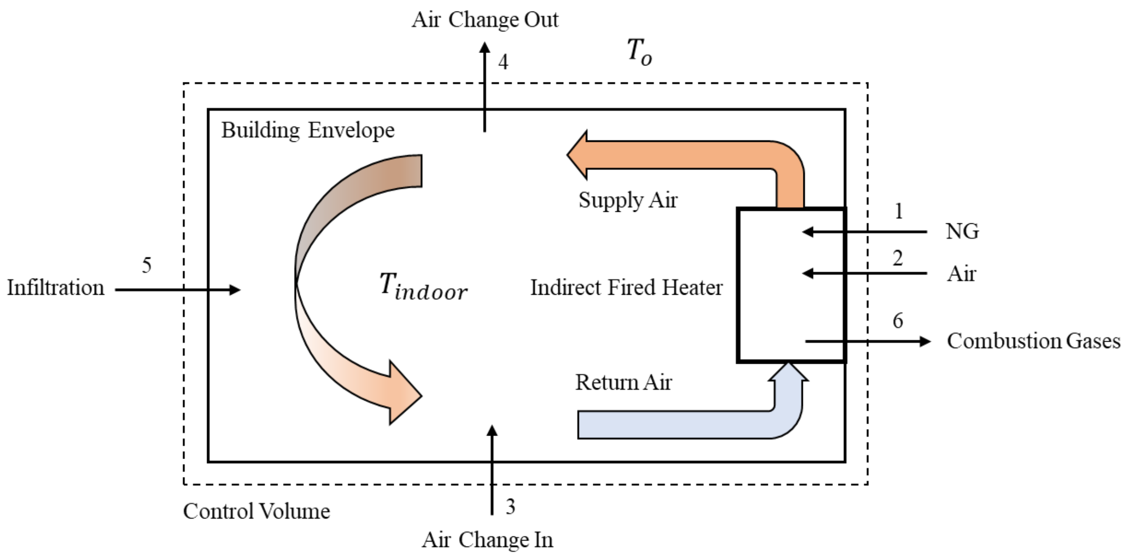


Fig. 4.1. Schematic diagram of indirect fired space heating system.

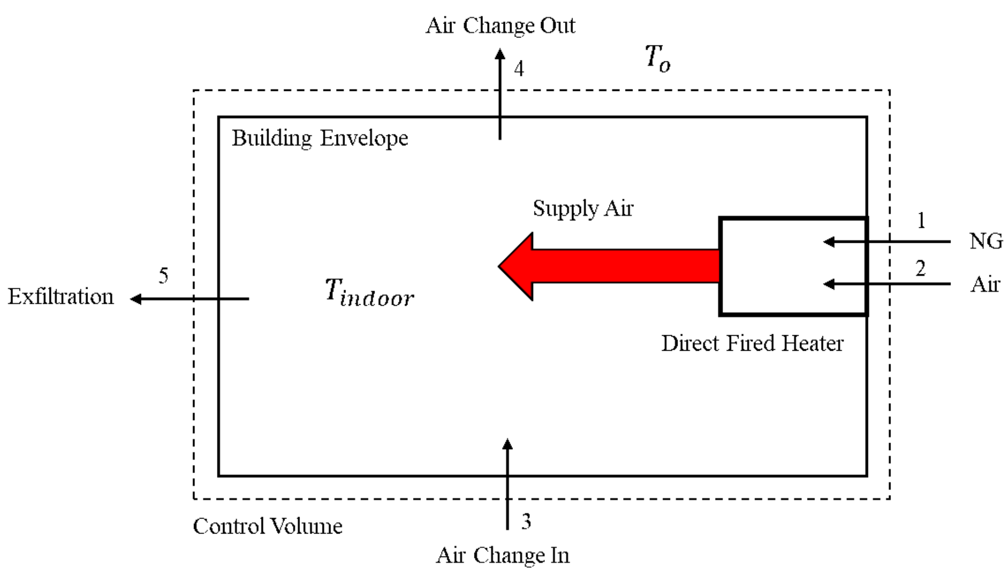


Fig. 4.2. Schematic diagram of direct fired space heating system.

4.3 Example System Setup

A 10,000 ft^2 in area, 20 ft high typical metal warehouse building is used to do the simulation and comparison between indirect and direct fired heaters based on the calculation models. Indoor temperature is controlled at 20°C. Outdoor temperature is an important parameter in a space heating system. In the study, it is set from -25°C to 10°C which is typical in winter. If the warehouse is only rarely occupied, the ventilation requirement has a range from 0 ACH to 1.5 ACH [25]. The device efficiency (AFUE) of indirect and direct fired heater is 80% and 92% respectively [26]. The direct fired heater fresh air volume flow rate is 3,500 CFM according to a proper heater selection for the system [27].

4.4 Assumptions

The following assumptions were made during the calculation in order to better control the simulation and the results will not be significantly affected.

4.4.1 General

The temperature and pressure of supply NG is set close to ambient temperature and pressure. The thermomechanical exergy of NG is also negligible because the temperature and pressure of NG at the point right before supplying to heaters are close to the ambient air temperature and pressure.

4.4.2 Indirect Fired Heating System

1. In indirect fired heating system, the excess air of the heater is 0%, which means the air flow is just adequate to make the combustion complete.

2. The exhaust temperature of indirect fired heater combustion gas is maintained at 182°C (360°F) [28].

3. The building is considered semi-tight building. The infiltration in indirect fired heating system is estimated as 0.2 ACH according to Air Conditioning Contractors of America (ACCA) commercial load calculation [29].

4.4.3 Direct Fired Heating System

1. Fresh air intake for direct fired heater can be considered as effective air change.

2. Constant air flow rate and constant supply air temperature.

4.4.4 Carbon Dioxide Concentration Level

1. The heating system is a steady system.

2. Air is ideal gas.

3. Carbon dioxide PPM change of air wont affect air density.

5. RESULTS AND DISCUSSION

Results based on simulation of models under certain conditions are introduced and discussed in this chapter, including results of systematic energy efficiency (under constant air flow rate and constant supply air temperature for direct fired heater), exergy efficiency, carbon dioxide concentration level and sensitivity of input parameters towards the systematic energy efficiency.

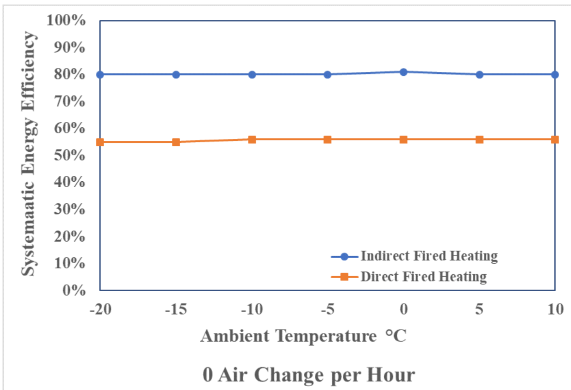
Air change requirement (ACH) showed in this chapter refers to the original system ventilation requirement and is not related to the air flow rate of direct fired heater. Its the amount of fresh air needed for this system without heating systems applied.

5.1 Systematic Energy Efficiency (Constant Air Flow Rate for Direct Fired Heater)

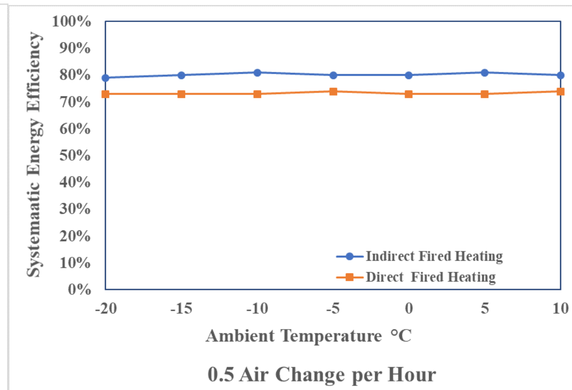
5.1.1 Systematic Energy Efficiency

The systematic energy efficiency calculation results for ambient temperature range from -20°C to 10°C and a ventilation air change rate per hour from 0 to 1.5 are shown in Figure 5.1. The results show that the systematic energy efficiency almost remains constant for both indirect and direct fired heating system at a certain air change requirement. To explain why the systematic energy efficiency doesn't change while ambient temperature varies, we need to refer to the definition of systematic energy efficiency in equation 3.2, which is a ratio of heating load and NG input. The heat load is a function of ΔT which is the difference between indoor and outdoor ambient temperature. According to energy balance , NG input in term of the rate of energy in kW (Btu/h) should be equal to the total heat rate delivered out of the building boundary divided by the heater device efficiency, its also a function of ΔT. So the impact of ΔT is cancelled when calculating the fraction of systematic energy efficiency.

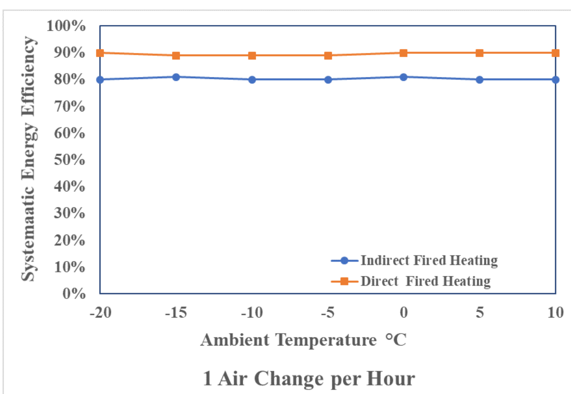
The systematic energy efficiency of indirect fired heating system is maintained at around 80% despite of the air change requirement. However, the systematic energy efficiency of direct fired heating system rises as air change rate increases. It reaches around 92% and will not exceed this point.



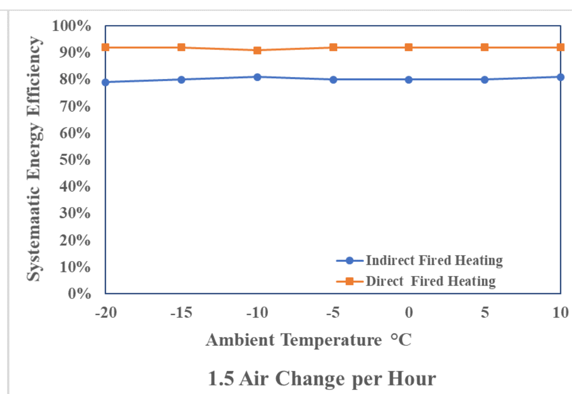
(a) 0 ACH



(b) 0.5 ACH



(c) 1 ACH



(d) 1.5 ACH

Fig. 5.1. Systematic energy efficiency vs. outdoor temperature under different air change requirement.

Figure 5.2 shows the comparison of systematic energy efficiency of indirect and direct fired heating system as the air change rate per hour increases between 0-1.5. An inflection point of air change rate exists that the indirect fired heating system is more efficient below this point, and the direct fired heating system is more efficient above this point. In this case study, the inflection point is at air change rate equals to 0.7 ACH. The reason is that direct fired heater applies 100% of outside air. When this amount of fresh air is not required, it results in more energy consumption used to heat up the fresh air. So the overall systematic energy efficiency is low.

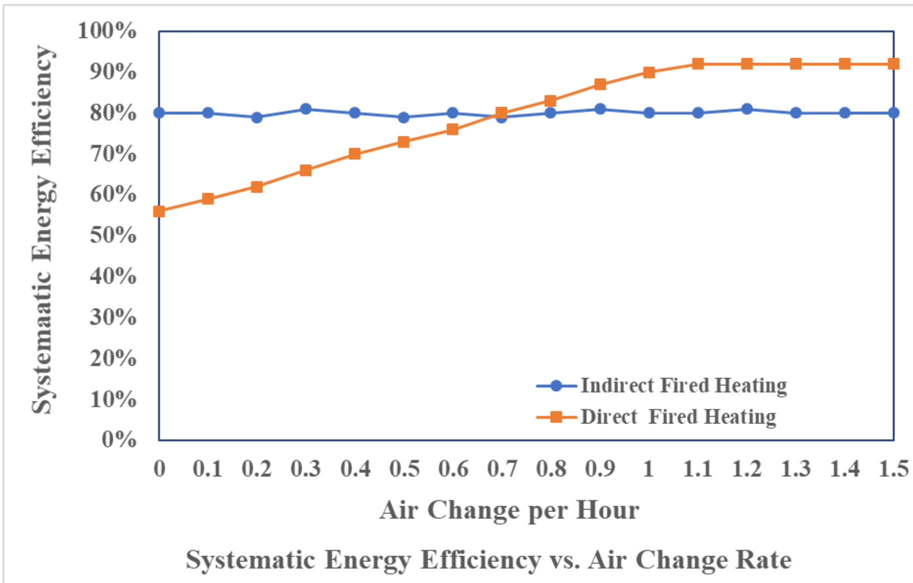
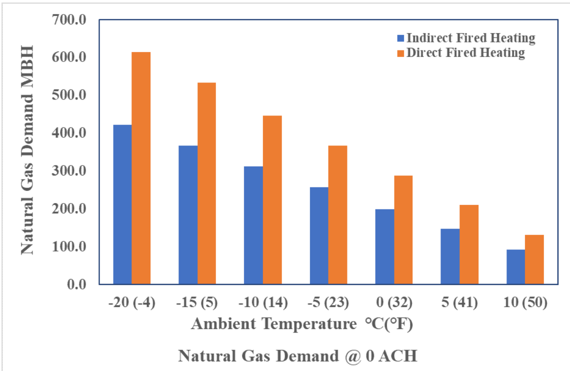


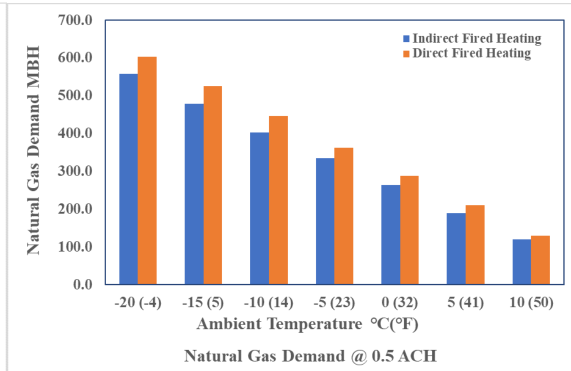
Fig. 5.2. Systematic energy efficiency vs. air change requirement.

5.1.2 Natural Gas Demand

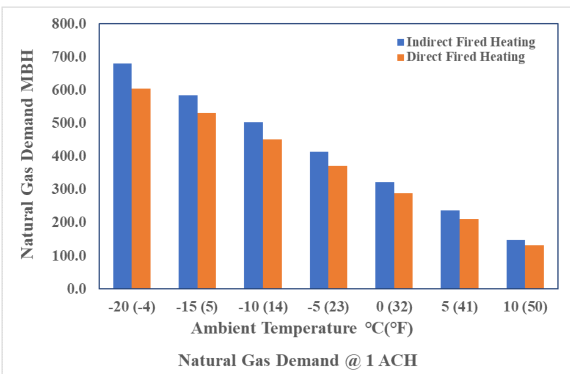
Figure 5.3 shows the natural gas demand comparison between indirect and direct fired heating system (constant air flow rate condition for direct fired heating system). The natural gas demands of indirect and direct fired heating system are related to both outdoor ambient temperature and required air change rate. Lower outdoor ambient temperature will result in higher natural gas demand for both heating systems. Lower air change rate will result in lower natural gas demand for indirect fired heating system. But for the direct fired heating system, the natural gas demand remains constant at a certain outdoor ambient temperature below the inflection point which is mentioned in section 5.1.1. Above this inflection point, the natural gas demand will increase as air change requirement increases from 0 to 1.5 ACH.



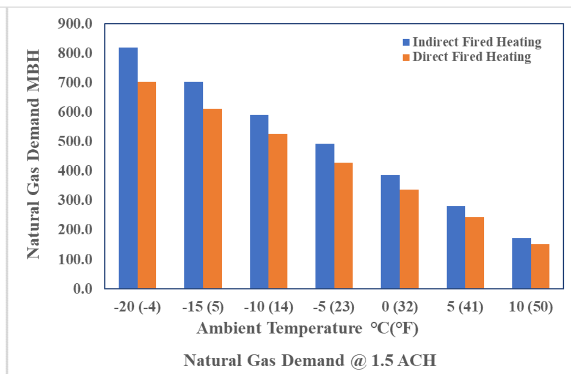
(a) 0 ACH



(b) 0.5 ACH



(c) 1 ACH



(d) 1.5 ACH

Fig. 5.3. Natural gas demand vs. outdoor temperature under different air change requirement.

5.1.3 Discussion

1. For indirect fired heating system, the systematic energy efficiency remains constant and not related to ambient temperature and air change requirement. The systematic efficiency is equal to the heater device efficiency.

2. For direct fired heating system under constant air flow rate condition, the systematic energy efficiency remains constant at different outdoor air temperature. Systematic energy efficiency increases as air change requirement goes higher and will finally reach the heater efficiency and maintain.

3. There is an inflection point related to air change requirement. Below this point, indirect fired heating system is more efficient. Above this point, direct fired heating system is more efficient.

4. The inflection point will be different according to different building type (heat loss coefficient, air change requirement).

5. At low air change requirement, indirect fired heating system has lower natural gas demand. As required air change rate rises, natural gas demand of direct fired heating system will decrease. When the air change requirement is higher than the inflection point, the natural gas demand of direct fired heating system will be lower than indirect fired heating system.

5.2 Systematic Energy Efficiency (Constant Supply Air Temperature for Direct Fired Heater)

5.2.1 Systematic Energy Efficiency

In this simulation, constant supply air temperature for direct fired heating system was applied. Under certain ambient temperature, the air flow rate of the heater might change in order to provide different amount of heat to the space. Results of different supply air temperatures under different ambient temperatures and air change requirement are compared.

The systematic energy efficiencies of direct fired heating system at certain supply air temperature are shown in Table 5.1-5.3 and Figure 5.4.

For direct fired heating system at constant supply air temperature, the systematic energy efficiency is related to ambient temperature, air change requirement and supply air temperature. Under a certain supply air temperature condition, rise of ambient temperature or air change requirement will increase the systematic energy efficiency. Once the systematic energy efficiency reaches the device efficiency (in this case, the device efficiency of direct fired heater is 92%), it will maintain.

Figure 5.5 shows the comparison of systematic energy efficiency at different supply air temperatures for direct fired heater. Lower supply air temperature will result in lower systematic energy efficiency. As what is discussed in the previous subsection, systematic energy efficiency will increase as ambient temperature and air change requirement increase. So at high air change requirement and ambient temperature, even under different supply air temperature, the systematic energy efficiency will tend to reach the device efficiency and maintain.

Figure 5.6 shows the air flow rate comparison between different supply air temperatures under various ambient temperatures. At higher supply air temperature condition, the required air flow rate will be lower. Under low ambient temperature condition, more air flow rate will be needed to provide enough heating capacity.

5.2.2 Natural Gas Demand

The natural gas demand of indirect fired heating system is shown in Table 5.4, while natural gas demand of direct fired heating system at certain supply air temperature are shown in Table 5.5-5.7, respectively. Figure 5.7 and 5.8 show the natural gas demand of indirect and direct fired heating systems charts at different conditions.

For both indirect and direct fired heating system, natural gas demands are related to ambient temperature and required air change rate. Lower ambient temperature will result in higher natural gas demand for both heating system. Lower air change rate will result in lower natural gas demand for indirect fired heating system. But for direct fired heating system, the natural gas demand remains constant at a certain ambient temperature when the supply air flow rate is higher than the air change requirement. When the supply air flow rate is lower than the air change requirement,

Table 5.1.
Systematic energy efficiency of direct fired heating system at 160°F supply air temperature at variable air change.

160°F Supply T	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	50.7%	51.8%	53.4%	55.8%	59.6%	62.6%	66.6%	70.7%	75.0%
0.25 Air Change	58.4%	59.7%	62.0%	64.6%	68.7%	72.4%	76.7%	80.9%	85.6%
0.5 Air Change	66.0%	67.5%	70.6%	73.4%	77.8%	82.2%	86.7%	91.1%	92.1%
0.75 Air Change	73.9%	75.7%	78.8%	81.8%	86.0%	89.4%	92.0%	91.6%	92.1%
1 Air Change	81.8%	83.9%	87.0%	90.2%	91.9%	92.0%	91.9%	92.0%	92.0%
1.25 Air Change	90.2%	92.0%	91.8%	91.9%	92.0%	92.1%	92.0%	92.1%	92.1%
1.5 Air Change	92.0%	92.0%	91.9%	91.9%	91.9%	92.0%	92.1%	92.1%	92.0%

Table 5.2.
Systematic energy efficiency of direct fired heating system at 140°F supply air temperature at variable air change.

140°F Supply T	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	45.0%	46.5%	48.1%	50.8%	54.3%	58.0%	63.0%	68.0%	74.0%
0.25 Air Change	51.5%	53.2%	55.5%	58.2%	62.1%	66.0%	71.2%	76.2%	82.7%
0.5 Air Change	59.1%	61.2%	63.4%	67.2%	71.2%	75.4%	80.9%	86.1%	91.9%
0.75 Air Change	66.1%	68.1%	70.9%	74.8%	79.6%	84.6%	90.7%	92.0%	92.0%
1 Air Change	73.1%	75.0%	78.4%	82.4%	87.9%	91.7%	91.8%	92.0%	92.1%
1.25 Air Change	80.1%	82.0%	85.1%	89.6%	92.0%	91.9%	92.0%	92.1%	92.0%
1.5 Air Change	87.0%	89.0%	91.7%	92.0%	91.9%	91.8%	92.0%	91.9%	92.0%

Table 5.3.
Systematic energy efficiency of direct fired heating system at 120°F supply air temperature at variable air change.

120°F Supply T	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
0.25 Air Change	45.0%	46.8%	48.7%	52.0%	55.7%	59.9%	65.0%	70.9%	77.9%
0.5 Air Change	51.0%	52.9%	55.2%	58.9%	63.1%	67.9%	73.6%	80.3%	88.2%
0.75 Air Change	56.9%	59.1%	61.6%	65.7%	70.5%	75.8%	82.1%	89.7%	91.8%
1 Air Change	62.9%	65.3%	68.0%	72.6%	77.8%	83.7%	90.7%	92.0%	92.0%
1.25 Air Change	68.8%	71.5%	74.5%	79.5%	85.2%	91.6%	91.8%	92.1%	92.0%
1.5 Air Change	74.8%	77.7%	80.9%	86.4%	91.9%	92.0%	92.0%	92.1%	92.0%

the natural gas demand will increase. Supply air flow rate is related to supply air temperature, ambient temperature and air change requirement.

Figure 5.9 shows comparison in natural gas demand between indirect and direct fired heating systems under different conditions. At low ambient temperature and low air change requirement, indirect fired heating system tends to have lower natural gas demand. As ambient temperature rises, the demand of direct fired heating system will drop more rapidly than indirect fired heating system and final drop below indirect fired heating system. And also, as the air change requirement rises, the demand of indirect fired heating system will increase more rapidly than direct fired heating system and finally rise above demand of direct fired heating system. When the air change requirement is higher than the air flow rate of direct fired heater, the systematic energy efficiency of direct fired heating will reach the highest point, 92%, which is the heater device efficiency according to the results in section 5.2.1. For indirect fired heating, the systematic energy efficiency is always constant at 80% according to the results in section 5.1.1. So with same heating load (boundary loss and air change loss are the same for both heating systems), the direct fired heating system has lower NG demand.

5.2.3 Discussion

1. For direct fired heating system at constant supply air temperature:
   - Under low air change requirement, the systematic energy efficiency will decrease as the outdoor temperature drops.
   - As the air change requirement increases, the systematic energy efficiency will increase and maintain at heater efficiency.
2. The higher the supply air temperature is, the higher the systematic energy efficiency of direct fired heating system will be.

Table 5.4.
Natural gas demand of indirect fired heating system at variable air change.

NG Demand of Indirect Fired Heating (MBH)	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	458.7	429.0	398.1	351.8	305.5	260.4	214.1	167.8	122.6
0.25 Air Change	528.6	494.3	458.7	405.4	352.1	300.0	246.7	193.4	141.3
0.5 Air Change	598.5	559.6	519.4	459.0	398.6	339.7	279.3	218.9	160.0
0.75 Air Change	668.3	625.0	580.0	512.6	445.2	379.4	311.9	244.5	178.7
1 Air Change	738.2	690.3	640.7	566.2	491.7	419.0	344.5	270.1	197.4
1.25 Air Change	808.1	755.7	701.3	619.8	538.3	458.7	377.2	295.6	216.0
1.5 Air Change	878.0	821.0	762.0	673.4	584.8	498.3	409.8	321.2	234.7

Table 5.5.
Natural gas demand of direct fired heating system at 160°F supply air temperature at variable air change.

NG Demand of Direct Fired Heating at 160°F Supply T (MBH)	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	713.7	648.3	583.3	491.1	405.3	327.8	254.7	188.0	129.1
0.25 Air Change	713.7	648.3	583.3	491.1	405.3	327.8	254.7	188.0	129.1
0.5 Air Change	713.7	648.3	583.3	491.1	405.3	327.8	254.7	190.4	139.1
0.75 Air Change	713.7	648.3	583.3	491.1	405.3	329.9	271.2	212.6	155.4
1 Air Change	713.7	648.3	583.3	492.3	427.6	364.4	299.6	234.8	171.6
1.25 Air Change	713.7	657.1	609.8	538.9	468.1	398.9	328.0	257.1	187.9
1.5 Air Change	763.4	713.9	662.6	585.6	508.5	433.3	356.3	279.3	204.1

Table 5.6.
Natural gas demand of direct fired heating system at 140°F supply air temperature at variable air change.

NG Demand of Direct Fired Heating at140°F Supply T (MBH)	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	796.8	721.0	645.9	540.0	442.2	354.5	272.8	199.1	135.0
0.25 Air Change	796.8	720.9	645.8	540.0	442.2	354.5	272.8	199.1	135.0
0.5 Air Change	796.8	720.9	645.8	539.9	442.2	354.5	272.8	199.1	139.1
0.75 Air Change	796.7	720.9	645.8	539.9	442.2	354.5	272.8	212.6	155.4
1 Air Change	796.7	720.9	645.8	539.9	442.1	364.4	299.6	234.8	171.6
1.25 Air Change	796.7	720.9	645.8	539.9	468.1	398.9	328.0	257.1	187.9
1.5 Air Change	796.7	720.9	662.6	585.6	508.5	433.3	356.3	279.3	204.1

Table 5.7.
Natural gas demand of direct fired heating system at 120°F supply air temperature at variable air change.

NG Demand of Direct Fired Heating at120°F Supply T (MBH)	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	939.4	845.6	753.2	623.8	505.4	400.5	303.8	218.2	145.2
0.25 Air Change	939.3	845.6	753.2	623.8	505.4	400.4	303.8	218.2	145.2
0.5 Air Change	939.3	845.6	753.2	623.8	505.4	400.4	303.8	218.2	145.2
0.75 Air Change	939.3	845.6	753.2	623.8	505.4	400.4	303.8	218.2	155.7
1 Air Change	939.3	845.6	753.2	623.8	505.4	400.4	303.8	234.8	171.6
1.25 Air Change	939.3	845.6	753.2	623.8	505.4	400.4	328.7	256.8	187.9
1.5 Air Change	939.3	845.6	753.2	623.8	509.1	433.3	356.3	279.0	204.1

3. At low air change requirement, the systematic energy efficiency of direct fired heating system will be much lower than the rated heater efficiency at low ambient temperature.

4. If maintain constant supply air temperature, at lower ambient temperature, the air flow rate will be higher. The air flow rate will be higher at lower supply air temperature setting.

5. For indirect fired heating system, the natural gas demand will increase as the ambient temperature drops and air change requirement rises.

6. For direct fired heating system, at low ambient temperature and low air change requirement, the gas demand remains constant under different air change requirement. But when the ambient temperature is higher than a point, high air change requirement will result in higher demand.

7. At low ambient temperature and low air change requirement, the low supply air temperature direct fired heating system has higher gas demand. As the ambient temperate or air change requirement increases, the gas demand of direct fired heating system under different supply air temperature will finally be the same.

8. At low ambient temperature and low air change requirement, indirect fired heating system has lower gas demand compared to direct fired heating system. As the ambient temperate or air change requirement increases, the gas demand of direct fired heating system will drop more rapidly than indirect fired heating system that the gas demand of direct fired heating system will become lower.

5.3 Exergy Efficiency

5.3.1 Systematic Exergy Efficiency

The systematic exergy efficiency calculation results under different ambient temperature and required air change per hour are shown in Figure 5.10. It can be noticed that the exergy efficiencies for both systems are very low, because in a heating system, high quality energy source (fossil fuel or electricity) is used to provide heat which is low quality energy. Also, exergy is destroyed when the heat is transferred through boundary. The temperature finally reaches ambient temperature which is the dead state, which means no thermomechanical exergy is available. Chemical exergy is very low for air. Thus, the exergy efficiency is very low.

The systematic exergy efficiency of indirect fired heating system is also higher than direct fired heating system. Its mainly caused by the relatively high temperature exhaust air from heaters. As air change rate increases, the exergy efficiency will rise. These features tell us that in indirect fired heating system, there is better chance to make use of waste heat, exhaust combustion air. In high air change rate application, there is also better chance to save energy and exergy by reclaiming heat from exhaust air due to air change.

5.3.2 Single Heater Exergy Efficiency

The exergy efficiencies of both single indirect fired and direct fired heater in close size were calculated based on 18.3°C (65°F) indoor space temperature. For direct fired heater, variable ambient temperature and supply air temperature were applied to the calculation. Figure 5.11 shows the results of single heater exergy efficiency for both heaters.

The single heater exergy efficiency of indirect fired heater is about 3.3% and not related to ambient temperature. The heater takes 100% return air inside the building. The input and output air temperatures are nearly constant, so the exergy efficiency is constant. For direct fired heater, single heater exergy efficiency is related to ambient temperature and supply air temperature. The exergy efficiency increases as the ambient temperature and supply air temperature rise. Under high ambient temperature condition, less natural gas input will be needed to maintain a certain supply air temperature that the exergy input for direct fired heater decreases and it contributes to the exergy efficiency the most. So the exergy efficiency will increase as the ambient temperature rises. The output exergy of the direct fired heater is mostly contributed by the thermomechanical exergy of air stream. Temperature of the supply air affects the thermomechanical exergy and the impact is larger than the increased natural gas input so that increased supply air temperature results in high exergy efficiency under a certain ambient temperature.

5.3.3 Discussion

1. The systematic exergy efficiencies for both systems are very low, because in a heating system, high quality energy source (fossil fuel) is used to provide heat which is low quality energy and exergy is destroyed when the heat is transferred through boundary.

2. The systematic exergy efficiency of indirect fired heating system is higher than direct fired heating system. Its mainly caused by the relatively high temperature exhaust air from heaters.

3. As air change rate increases, the systematic exergy efficiency will rise. It tells us that in indirect fired heating system, there is better chance to make use of waste heat, exhaust combustion air. In high air change rate application, there is also better chance to save energy and exergy by reclaiming heat from exhaust air due to air change.

4. The single heater exergy efficiency of indirect fired heater is about 3.3% and not related to ambient temperature. The heater takes 100% return air inside the building. The input and output air temperatures are nearly constant, so the exergy efficiency is constant.

5. For direct fired heater, single heater exergy efficiency is related to ambient temperature and supply air temperature. Single heater exergy efficiency will

rise as ambient temperature increases. Single heater exergy efficiency will rise as supply air temperature rises.

5.4 Carbon Dioxide Concentration Level

Carbon dioxide concentration level in the space will be affected by combustion of direct fired heaters. In this section, indoor carbon dioxide concentration level using direct fired heating system will be studied and discussed. For indirect fired heating system, indoor carbon dioxide concentration level wont be affected by heating devices since combustion of indirect fired heaters is isolated from indoor return air.

5.4.1 Constant Air Flow Rate for Direct Fired Heater

Based on the constant air flow rate of direct fired heater scenario, carbon dioxide concentration in the space can be calculated. Table 5.8 and Figure 5.12 show the carbon dioxide concentration level in PPM under different air change requirement and ambient temperature condition. Under low ambient temperature and air change requirement, the carbon dioxide PPM is high according to higher natural gas input and less fresh air into the space.

When the required air change rate is less than the air flow rate of direct fired heater, the carbon dioxide PPM in the space keeps constant under different air change requirement. But as ambient temperature rises, the indoor carbon dioxide PPM will drop. When the required air change rate is higher than the air flow rate of direct fired heater, the higher the air change rate is, the lower the indoor carbon dioxide PPM is.

5.4.2 Constant Supply Air Temperature for Direct Fired Heater

Based on the constant supply air temperature of direct fired heating system scenario, the carbon dioxide concentration level in the space can be calculated. Table 5.9-5.11 and Figure 5.13-5.15 show the carbon dioxide concentration level in PPM

Table 5.8.
Indoor carbon dioxide PPM under different air change requirement and ambient temperature.

CO_2 (PPM)	Ambient T °C (°F)						
	-20 (-4)	-15 (5)	-10 (14)	-5 (23)	0 (32)	5 (41)	10 (50)
0 Air Change	4392.5	3874.4	3303.6	2794.2	2284.5	1774.5	1264.2
0.5 Air Change	4324.8	3815.6	3306.0	2764.0	2286.0	1775.6	1253.4
1 Air Change	4236.9	3855.5	3340.0	2824.2	2287.0	1776.3	1265.3
1.5 Air Change	3599.8	3184.8	2795.4	2354.2	1938.6	1522.8	1106.8

Table 5.9.
Indoor carbon dioxide PPM under different air change requirement and ambient temperature (120°F supply air temperature).

Direct Fired Heating at 120°F Supply T	Ambient T°C (°F)				
	-23.3 (-10)	-17.8 (0)	-9.4 (15)	-1.1 (30)	7.2 (45)
0 Air Change	3749.5	3464.4	3007.1	2539.9	2090.7
0.25 Air Change	3749.4	3464.3	3007.0	2539.9	2090.6
0.5 Air Change	3749.3	3464.2	3007.0	2539.8	2090.6
0.75 Air Change	3749.3	3464.2	3007.0	2539.8	1826.2
1 Air Change	3749.2	3464.1	3006.9	2480.0	1581.3
1.25 Air Change	3749.2	3464.1	3006.9	2202.4	1436.2
1.5 Air Change	3749.2	3464.1	2721.9	2029.7	1339.5

under different air change requirement and outdoor ambient temperature condition, 120°F, 140°F, 160°F supply air temperature respectively.

When the required air change rate is less than the air flow rate of direct fired heater, the carbon dioxide PPM in the space keeps constant under different air change requirement. As ambient temperature rises, the indoor carbon dioxide PPM will drop. Because less natural gas will be needed under higher ambient temperature condition. When the required air change rate is higher than the air flow rate of direct fired heater, the higher the air change rate is, the lower the indoor carbon dioxide PPM is. More air change rate results in higher indoor air quality.

Table 5.10.
Indoor carbon dioxide PPM under different air change requirement and ambient temperature (140°F supply air temperature).

Direct Fired Heating at 140°F Supply T	Ambient T °C (°F)				
	-23.3 (-10)	-17.8 (0)	-9.4 (15)	-1.1 (30)	7.2 (45)
0 Air Change	3773.4	3556.4	3211.5	2879.0	2549.6
0.25 Air Change	3773.4	3556.4	3211.4	2878.9	2549.6
0.5 Air Change	3773.3	3556.3	3211.4	2878.9	2306.5
0.75 Air Change	3773.2	3556.3	3211.3	2878.9	1823.1
1 Air Change	3773.2	3556.2	3211.3	2451.6	1581.3
1.25 Air Change	3773.2	3556.2	2960.1	2198.5	1436.2
1.5 Air Change	3773.1	3416.9	2719.4	2029.7	1339.5

Table 5.11.
Indoor carbon dioxide PPM under different air change requirement and ambient temperature (160°F supply air temperature).

Direct Fired Heating at 160°F Supply T	Ambient T °C (°F)				
	-23.3 (-10)	-17.8 (0)	-9.4 (15)	-1.1 (30)	7.2 (45)
0 Air Change	4224.5	4008.4	3661.4	3329.0	3001.4
0.25 Air Change	4224.4	4008.3	3661.3	3328.9	3001.3
0.5 Air Change	4224.3	4008.2	3661.2	3328.9	2306.5
0.75 Air Change	4224.3	4008.2	3661.2	2873.2	1823.1
1 Air Change	4224.2	4008.1	3321.0	2451.6	1581.3
1.25 Air Change	4224.2	3730.2	2960.1	2198.5	1436.2
1.5 Air Change	3873.3	3416.9	2719.4	2029.7	1339.5

5.4.3 Carbon Dioxide Concentration Requirement

According to ASHRAE standard 62.1-2013, carbon dioxide concentration is indicated as poor over 1,500 PPM [11]. For the direct fired heating system, even we dont consider carbon dioxide generated by human and production, the PPM of carbon dioxide indoor will easily get higher than 1,500 based on the results of the example case. When using indirect fired heater, the indoor air quality wont be affected by the combustion, so more fresh air (air change rate) will be required while using direct fired heater to maintain the indoor air quality. Extra fresh air above normal fresh air requirement will lower the systematic energy efficiency of the heating system.

5.4.4 Discussion

1. For direct fired heating system, indoor carbon dioxide PPM will be increased due to combustion of natural gas.

2. Under constant air flow rate condition, indoor carbon dioxide PPM will increase as the ambient temperature drops. When the air change requirement is less than heater air flow rate, the indoor carbon dioxide PPM remains the same under different air change rate at certain ambient air temperature. When the air change requirement is higher than heater air flow rate, the indoor carbon dioxide PPM will decrease as the air change rate rises.

3. Under constant supply air temperature condition, when the required air change rate is less than the air flow rate of direct fired heater, the carbon dioxide PPM in the space keeps constant under different air change requirement. As ambient temperature rises, the indoor carbon dioxide PPM will drop.

4. Indoor carbon dioxide PPM when using direct fired heating system will easily rise above 1,500 PPM that the air quality is considered poor. So extra fresh air needs to be applied. The systematic energy efficiency of the system will go even lower.

Table 5.12.
Parameters affecting carbon dioxide concentration.

Constant Air Flow Rate Condition	**Constant Supply Air Temperature Condition**
Heat Loss Coefficient	Heat Loss Coefficient
Ambient Temperature	Ambient Temperature
Air Change Rate	Air Change Rate

5.5 Sensitivity Analysis of Input Parameters Towards Systematic Energy Efficiency of Direct Fired Heating System

There are several input parameters which will affect the systematic energy efficiency of the direct fired heating system such as ambient air temperature, air change requirement, heat loss coefficient through envelope, etc.

Sensitivity analysis is conducted to evaluate the sensitivity of each input parameters to the systematic energy efficiency.

Input parameters which are related to systematic energy efficiency under constant air flow rate condition and constant supply air condition are listed in Table 5.12.

5.5.1 Constant Air Flow Rate

Under constant air flow rate of direct fired heater condition. Calculation results in section 4.1 are used as the benchmark in this sensitivity analysis.

Heat Loss Coefficient

Table 5.13 shows the sensitivity of heat loss coefficient under different air change requirement and ambient temperature. The sensitivity of heat loss coefficient is not related to ambient temperature. Its only related to air change requirement. At low air change requirement, systematic energy efficiency is more sensitive to the heat loss coefficient. The sensitivity is 0.452 at 0 air change. As air change requirement increases, the sensitivity will decrease from 0.452 to 0. When the air change requirement is higher than air flow rate of direct fired heater, the sensitivity will drop to 0 which means the heat loss coefficient change will no long affect the systematic energy efficiency.

Ambient Temperature

From the results in section 4.1.1, we know that under constant air flow rate condition, systematic energy efficiency is not related to ambient temperature, so the sensitivity of ambient temperature is 0.

Air Change Requirement

Table 5.14 shows the sensitivity of air change requirement under different air change requirement and ambient temperature. The sensitivity of air change requirement is not related to ambient temperature. Its only related to basic air change requirement. At low air change requirement, systematic energy efficiency is less sensitive to air change requirement. As air change requirement increases, the sensitivity will increase from 0.006 to 0.379. When the air change requirement is higher than air flow rate of direct fired heater, the sensitivity will drop to 0 which means the change of air change requirement will no long affect the systematic energy efficiency.

Sensitivity Comparison

Figure 5.16 shows the sensitivity comparison between the air change requirement and the heat loss coefficient in this scenario. Both are not related to ambient temperature but only to the air change requirement. At low air change requirement baseline, the heat loss coefficient has dominant sensitivity towards the systematic energy effi-

Table 5.13.
Sensitivity of heat loss coefficient (constant air flow rate).

Air Change Requirement (ACH)	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.452	0.452	0.452	0.452	0.452	0.452	0.452	0.452	0.452
0.25 ACH	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299
0.5 ACH	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181
0.75 ACH	0.089	0.089	0.089	0.089	0.089	0.089	0.089	0.089	0.089
1 ACH	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
1.25 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.5 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5.14.
Sensitivity of air change requirement (constant air flow rate).

Air Change Requirement (ACH)	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
0.25 ACH	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132
0.5 ACH	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234
0.75 ACH	0.314	0.314	0.314	0.314	0.314	0.314	0.314	0.314	0.314
1 ACH	0.379	0.379	0.379	0.379	0.379	0.379	0.379	0.379	0.379
1.25 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.5 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

ciency. As air change requirement baseline increases, the sensitivity of the heat loss coefficient drops while sensitivity of the air change requirement rises.

5.5.2 Constant Supply Air Temperature

Under constant supply air temperature of direct fired heater condition. Calculation results in section 5.2 are used as the benchmark in this sensitivity analysis.

Heat Loss Coefficient

Table 5.15-5.17 and Figure 5.17-5.19 show the sensitivity of heat loss coefficient under different air change requirement and ambient temperature, at 120, 140 and 160 supply air temperature respectively. Negative number means that while heat loss coefficient increase, the systematic energy efficiency will drop and vice versa.

At 0 air change, the sensitivity is 0. As air change increases at a certain ambient temperature, the sensitivity will firstly increase and then decrease to 0 again. At a certain air change rate, from low to high ambient temperature, the sensitivity will firstly remain and then drop to 0 gradually.

When the ambient temperature is low enough, the supply air temperature wont affect the sensitivity. But the higher the supply air temperature is, at lower ambient temperature will the sensitivity drop at a certain air change rate.

Ambient Temperature

Table 5.18-5.20 and Figure 5.20-5.22 show the sensitivity of ambient air temperature under different air change requirement and ambient temperature baseline, at 120°F, 140°F and 160°F supply air temperature respectively.

At a certain air change rate, sensitivity will increase gradually as the ambient temperature baseline increases. But after the air change rate goes higher than supply air flow rate, the sensitivity will drop to 0 eventually. At a certain ambient temperature

Table 5.15.
Sensitivity of heat loss coefficient at 120°F supply air temperature.

120°F Supply Air Temp	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.25 ACH	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171
0.5 ACH	-0.302	-0.302	-0.302	-0.302	-0.302	-0.302	-0.302	-0.302	-0.193
0.75 ACH	-0.405	-0.405	-0.405	-0.405	-0.405	-0.405	-0.405	-0.116	0.000
1 ACH	-0.489	-0.489	-0.489	-0.489	-0.489	-0.438	-0.062	0.000	0.000
1.25 ACH	-0.558	-0.558	-0.558	-0.558	-0.353	-0.017	0.000	0.000	0.000
1.5 ACH	-0.617	-0.617	-0.606	-0.289	0.000	0.000	0.000	0.000	0.000

Table 5.16.
Sensitivity of heat loss coefficient at 140°F supply air temperature.

140 Supply Air Temp	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.25 ACH	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171
0.5 ACH	-0.302	-0.302	-0.302	-0.302	-0.302	-0.302	-0.302	-0.203	0.000
0.75 ACH	-0.405	-0.405	-0.405	-0.405	-0.405	-0.331	-0.025	0.000	0.000
1 ACH	-0.489	-0.489	-0.489	-0.428	-0.151	0.000	0.000	0.000	0.000
1.25 ACH	-0.558	-0.430	-0.261	-0.008	0.000	0.000	0.000	0.000	0.000
1.5 ACH	-0.193	-0.043	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5.17.
Sensitivity of heat loss coefficient at 160°F supply air temperature.

160 Supply Air Temp	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.25 ACH	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171
0.5 ACH	-0.302	-0.302	-0.302	-0.302	-0.302	-0.302	-0.215	0.000	0.000
0.75 ACH	-0.405	-0.405	-0.405	-0.405	-0.208	0.000	0.000	0.000	0.000
1 ACH	-0.489	-0.354	-0.208	0.000	0.000	0.000	0.000	0.000	0.000
1.25 ACH	-0.069	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.5 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

baseline, sensitivity maintains as air change rate increases. But after the air change rate goes higher than the supply air flow rate, the sensitivity will drop to 0.

Air Change Requirement

Table 5.21-5.23 and Figure 5.23-5.25 show the sensitivity of air change requirement under different air change requirement and ambient temperature, at 120°F, 140°F and 160°F supply air temperature respectively.

At 0 air change, the sensitivity is almost 0. As air change increases at a certain ambient temperature, the sensitivity will firstly increase and then decrease to 0 again once the air change rate exceeds the supply air flow rate of heater. At a certain air change rate, from low to high ambient temperature, the sensitivity will firstly remain and then drop to 0 gradually.

When the ambient temperature is low enough, the supply air temperature wont affect the sensitivity. But the higher the supply air temperature is, at lower ambient temperature will the sensitivity drop at a certain air change rate.

Sensitivity Comparison

Heat loss coefficient and air change requirement have very similar sensitivity upon systematic energy efficiency. The difference between them is that heat loss coefficient has negative sensitivity (increase of heat loss coefficient will decrease systematic energy efficiency), and air change requirement has positive sensitivity (increase of air change requirement will increase systematic energy efficiency). Ambient temperature has relatively higher sensitivity compared to heat loss coefficient and air change requirement.

Table 5.18.
Sensitivity of ambient temp at 120°F supply air temperature.

120°F Supply Air Temp	Ambient T °F (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	3.504	3.681	3.881	4.213	4.595	5.025	5.541	6.153	6.871
0.25 ACH	3.504	3.681	3.881	4.213	4.595	5.025	5.541	6.153	6.871
0.5 ACH	3.504	3.681	3.881	4.213	4.595	5.025	5.541	6.153	6.871
0.75 ACH	3.504	3.681	3.881	4.213	4.595	5.025	5.541	6.153	0.000
1 ACH	3.504	3.681	3.881	4.213	4.595	5.025	3.800	0.000	0.000
1.25 ACH	3.504	3.681	3.881	4.213	4.595	1.053	0.000	0.000	0.000
1.5 ACH	3.504	3.681	3.881	4.213	0.000	0.000	0.000	0.000	0.000

Table 5.19.
Sensitivity of ambient temp at 140°F supply air temperature.

140°F Supply Air Temp	Ambient T °F (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	3.036	3.173	3.325	3.575	3.856	4.166	4.527	4.942	5.412
0.25 ACH	3.036	3.173	3.325	3.575	3.856	4.166	4.527	4.942	5.412
0.5 ACH	3.036	3.173	3.325	3.575	3.856	4.166	4.527	4.942	0.000
0.75 ACH	3.036	3.173	3.325	3.575	3.856	4.166	1.521	0.000	0.000
1 ACH	3.036	3.173	3.325	3.575	3.856	0.000	0.000	0.000	0.000
1.25 ACH	3.036	3.173	3.325	0.469	0.000	0.000	0.000	0.000	0.000
1.5 ACH	3.036	2.466	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5.20.
Sensitivity of ambient temp at 160°F supply air temperature.

160°F Supply Air Temp	Ambient T °F (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	2.678	2.788	2.908	3.105	3.322	3.557	3.826	4.129	4.464
0.25 ACH	2.678	2.788	2.908	3.105	3.322	3.557	3.826	4.129	4.464
0.5 ACH	2.678	2.788	2.908	3.105	3.322	3.557	3.826	0.000	0.000
0.75 ACH	2.678	2.788	2.908	3.105	3.322	0.000	0.000	0.000	0.000
1 ACH	2.678	2.788	2.908	0.000	0.000	0.000	0.000	0.000	0.000
1.25 ACH	2.678	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.5 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5.21.
Sensitivity of ambient temp at 120°F supply air temperature.

120°F Supply Air Temp	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
0.25 ACH	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132
0.5 ACH	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234
0.75 ACH	0.314	0.314	0.314	0.314	0.314	0.314	0.314	0.314	0.000
1 ACH	0.379	0.379	0.379	0.379	0.379	0.379	0.379	0.000	0.000
1.25 ACH	0.432	0.432	0.432	0.432	0.432	0.432	0.000	0.000	0.000
1.5 ACH	0.478	0.478	0.478	0.478	0.000	0.000	0.000	0.000	0.000

Table 5.22.
Sensitivity of ambient temp at 140°F supply air temperature.

140°F Supply Air Temp	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
0.25 ACH	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132
0.5 ACH	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.000
0.75 ACH	0.314	0.314	0.314	0.314	0.314	0.314	0.314	0.000	0.000
1 ACH	0.379	0.379	0.379	0.379	0.379	0.000	0.000	0.000	0.000
1.25 ACH	0.432	0.432	0.432	0.226	0.000	0.000	0.000	0.000	0.000
1.5 ACH	0.478	0.478	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 5.23.
Sensitivity of ambient temp at 160°F supply air temperature.

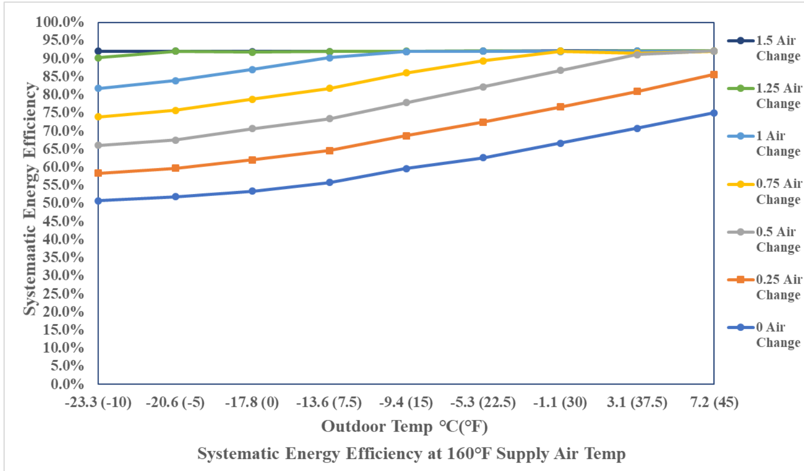
160°F Supply Air Temp	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
0.25 ACH	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132
0.5 ACH	0.234	0.234	0.234	0.234	0.234	0.234	0.234	0.000	0.000
0.75 ACH	0.314	0.314	0.314	0.314	0.314	0.000	0.000	0.000	0.000
1 ACH	0.379	0.379	0.379	0.000	0.000	0.000	0.000	0.000	0.000
1.25 ACH	0.432	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.5 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

5.5.3 Discussion

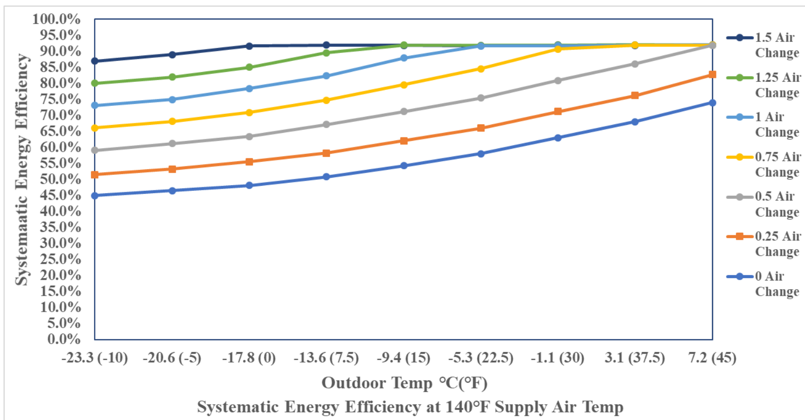
1. Under constant air flow rate condition, sensitivity of ambient temperature is 0. At low air change requirement baseline, heat loss coefficient has dominant sensitivity towards the systematic energy efficiency. As air change requirement baseline increases, sensitivity of heat loss coefficient drops while sensitivity of air change requirement rises.

2. Under constant supply air temperature condition, heat loss coefficient and air change requirement have very similar sensitivity upon systematic energy efficiency. The difference between them is that heat loss coefficient has negative sensitivity (increase of heat loss coefficient will decrease systematic energy efficiency), and air change requirement has positive sensitivity (increase of air change requirement will increase systematic energy efficiency).

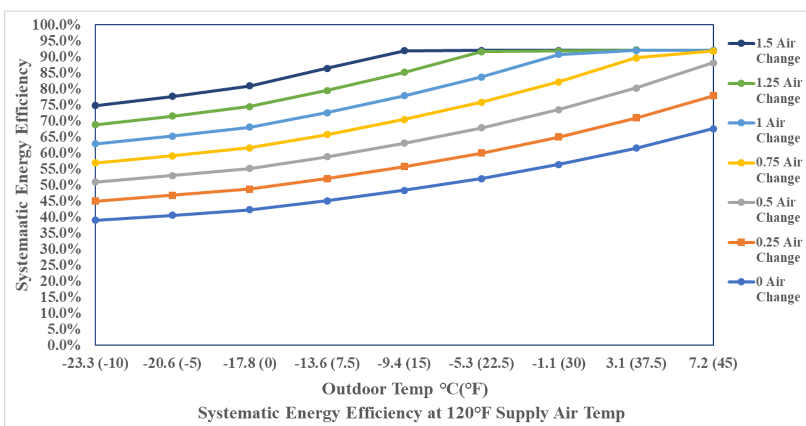
3. Under constant supply air temperature condition, ambient temperature has relatively higher sensitivity compared to heat loss coefficient and air change requirement.



(a) 160˚F Supply Air Temp

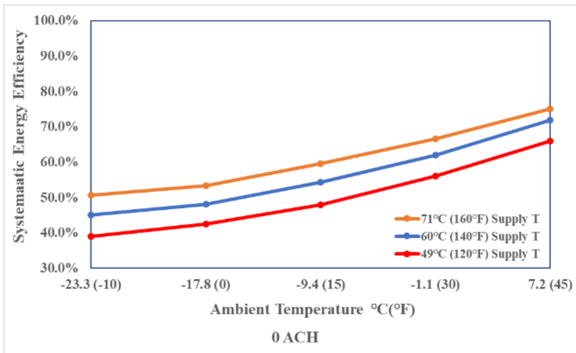


(b) 140˚F Supply Air Temp

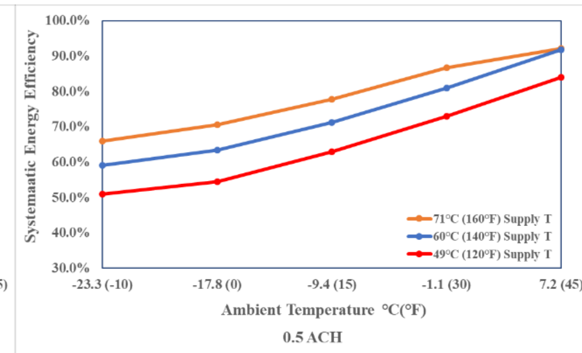


(c) 120˚F Supply Air Temp

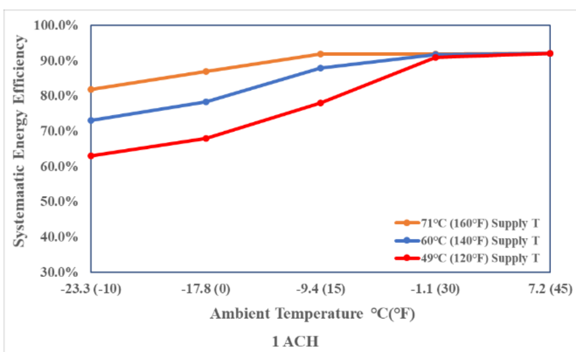
Fig. 5.4. Systematic energy efficiency for direct fired heating system vs. outdoor air temperature under different air change requirement at different supply air temp.



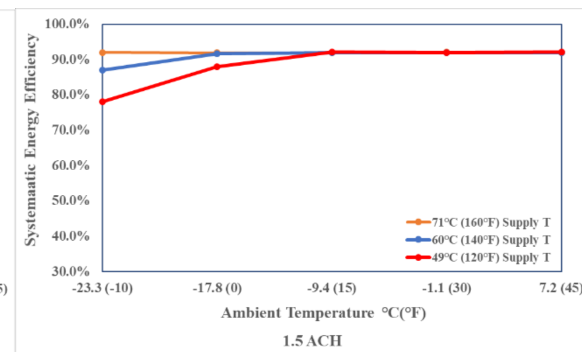
(a) 0 ACH



(b) 0.5 ACH



(c) 1 ACH



(d) 1.5 ACH

Fig. 5.5. Systematic energy efficiency for direct fired heating system vs. outdoor air temperature under different supply air temperature.

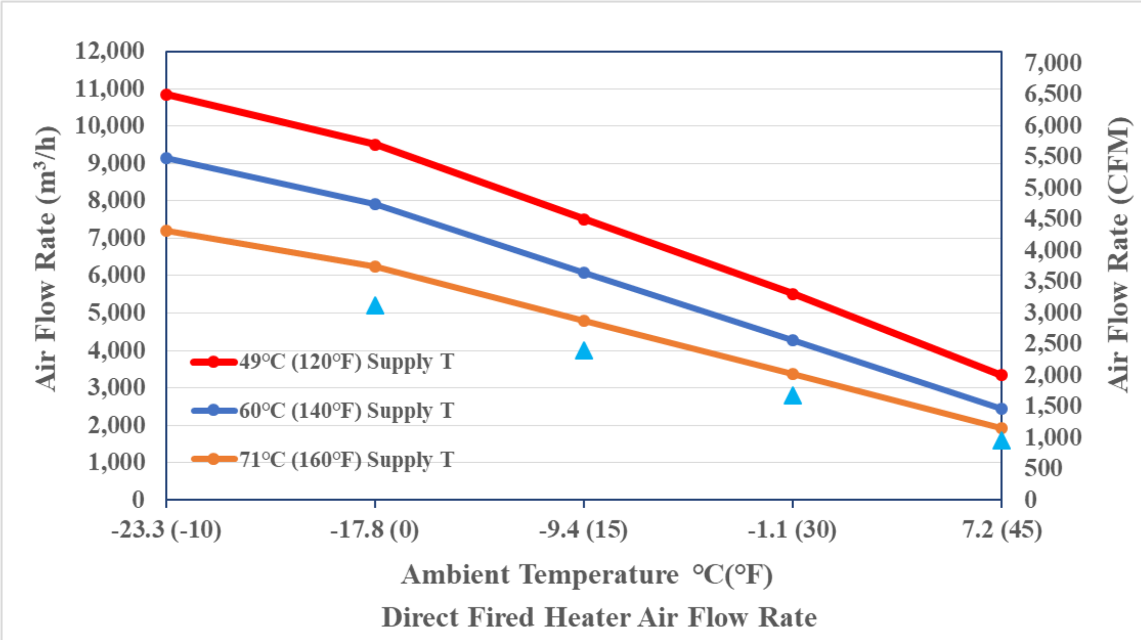


Fig. 5.6. Direct fired heater air flow rate vs. outdoor air temperature.

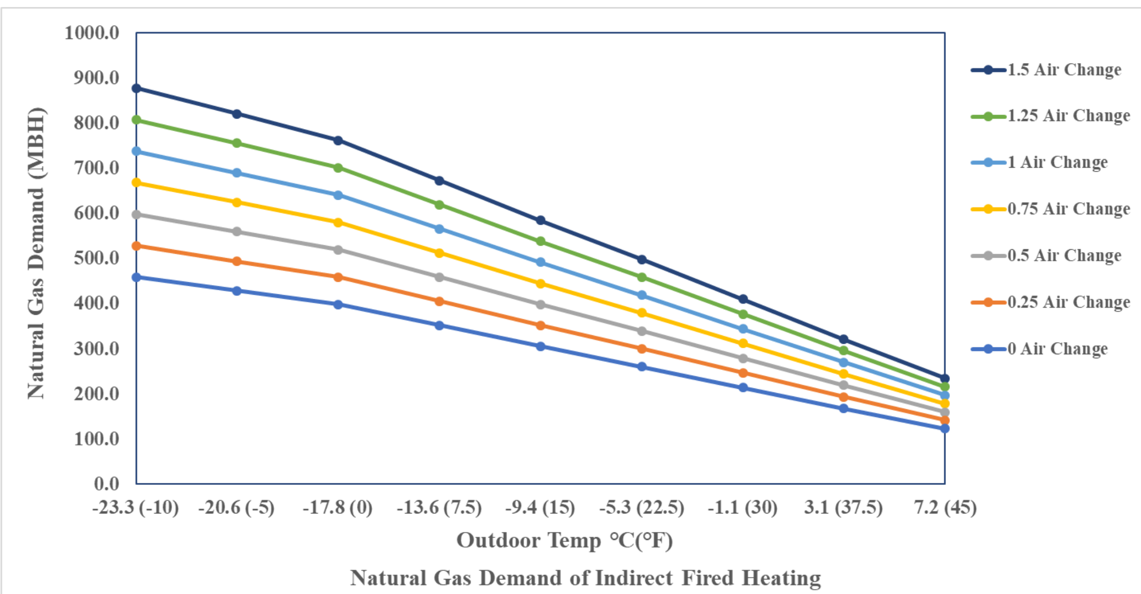
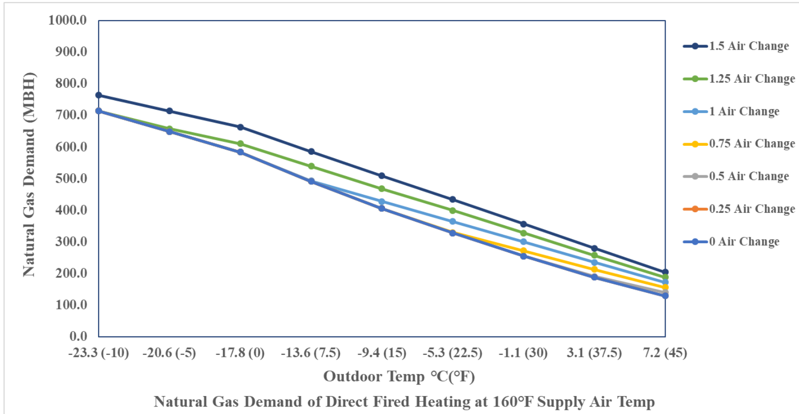
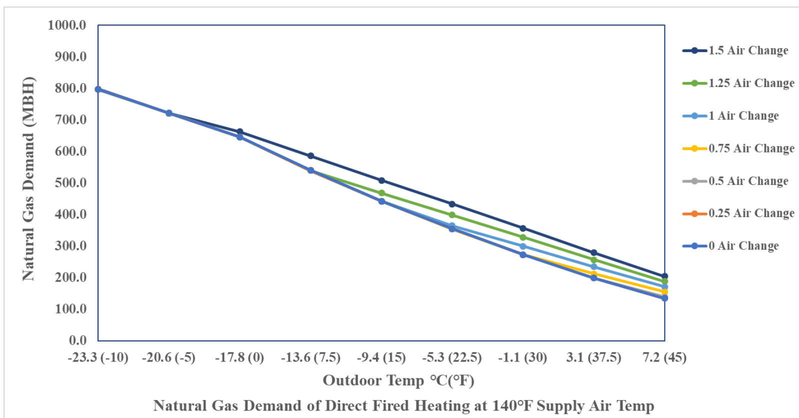


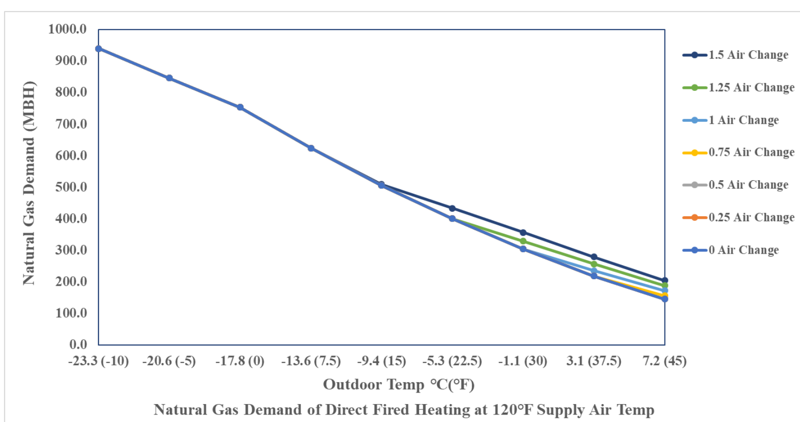
Fig. 5.7. Natural gas demand for indirect fired heating system vs. outdoor air temperature under different air change requirement.



(a) 160°F Supply Air Temp

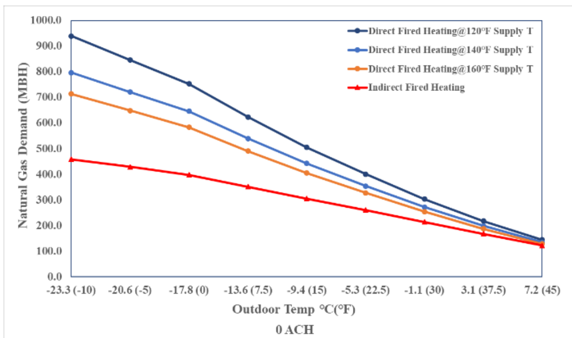


(b) 140°F Supply Air Temp

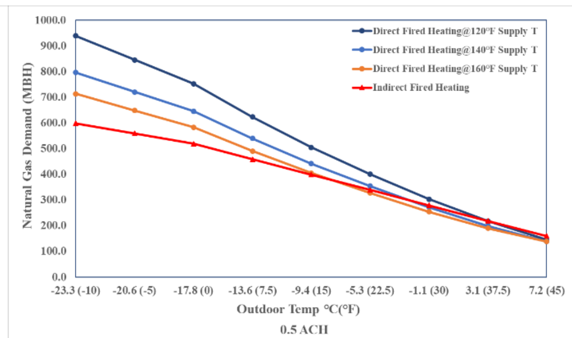


(c) 120°F Supply Air Temp

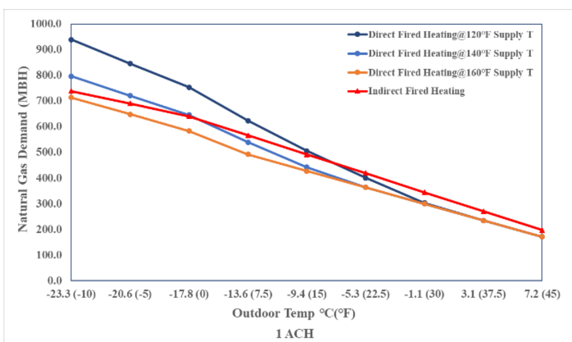
Fig. 5.8. Natural gas demand for direct fired heating system vs. outdoor air temperature under different air change requirement.



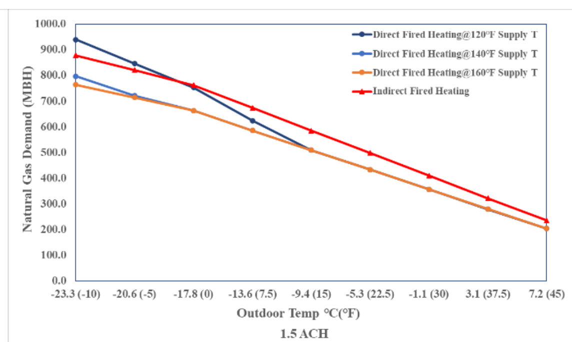
(a) 0 ACH



(b) 0.5 ACH

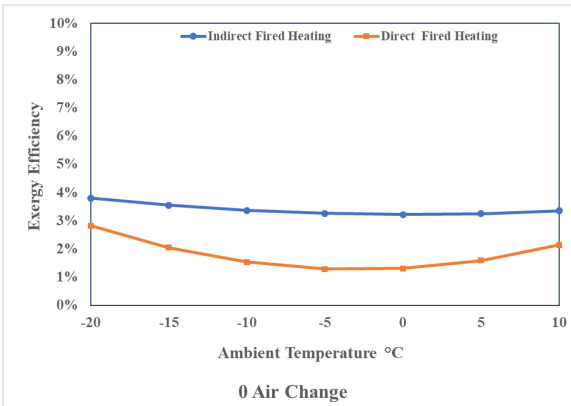


(c) 1 ACH

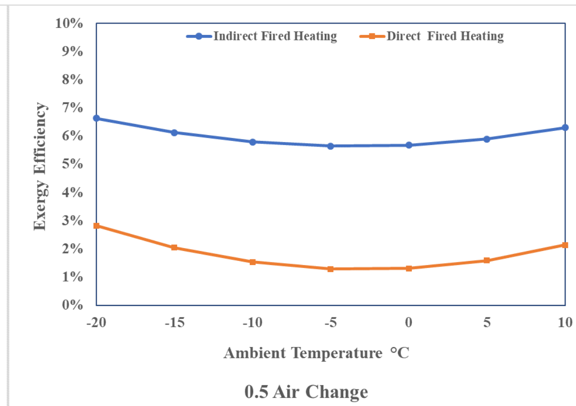


(d) 1.5 ACH

Fig. 5.9. Natural gas demand comparison between direct fired heating system.



(a) 0 ACH



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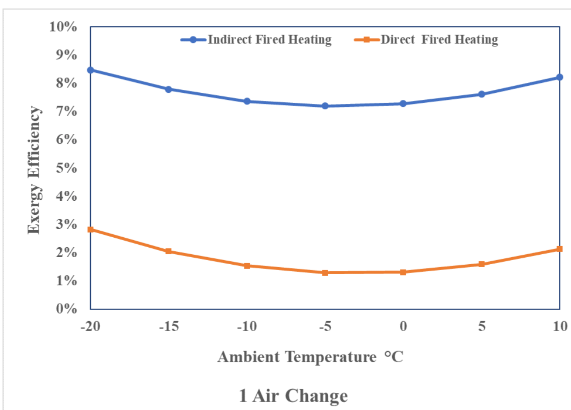
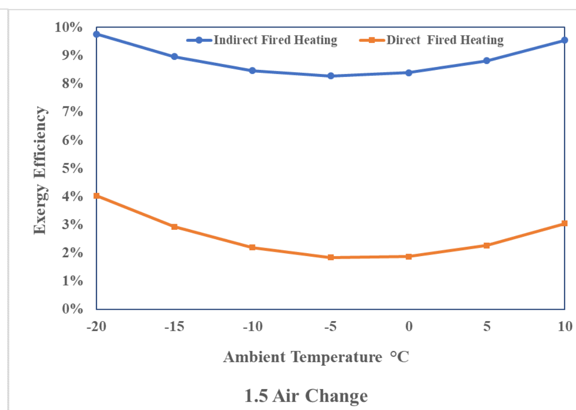


(c) 1 ACH



(d) 1.5 ACH

Fig. 5.10. Systematic exergy efficiency.

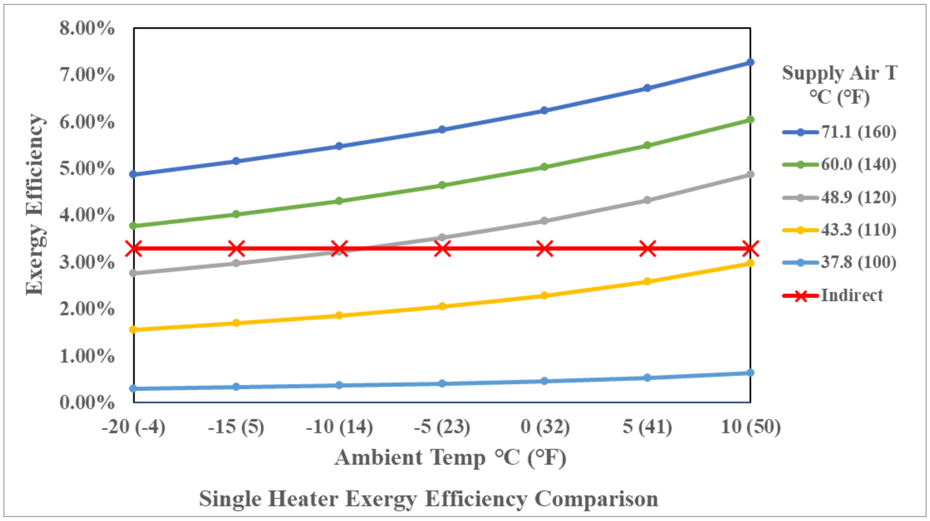


Fig. 5.11. Single heater exergy efficiency.

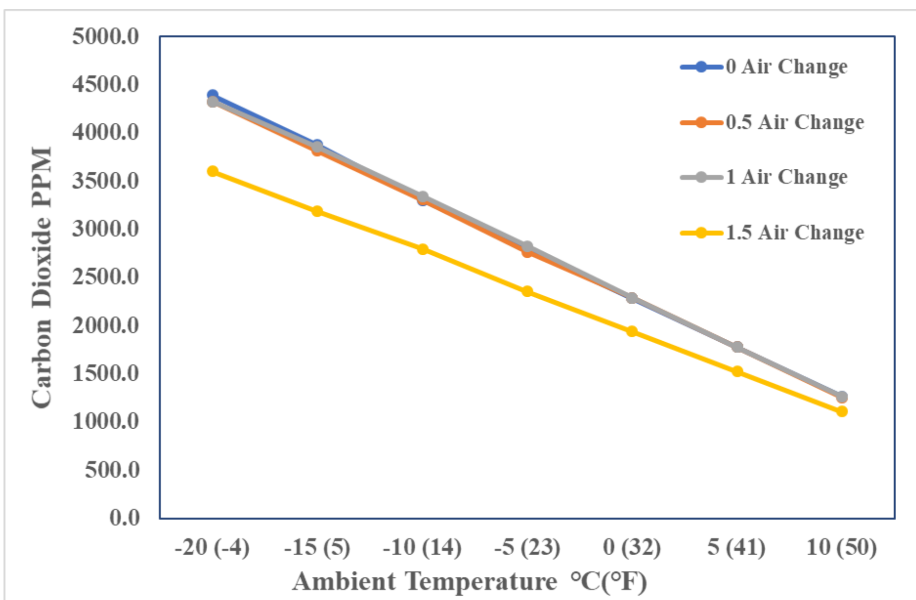


Fig. 5.12. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature.

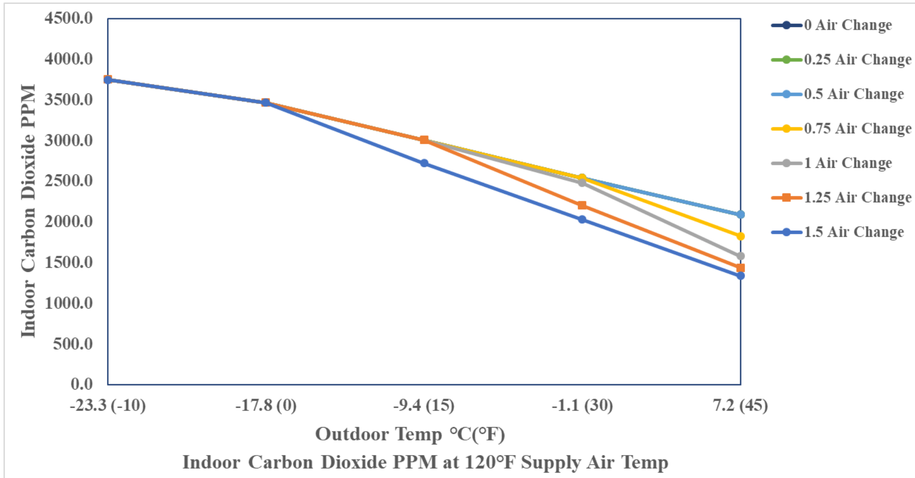


Fig. 5.13. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature at 120°F supply air temperature.

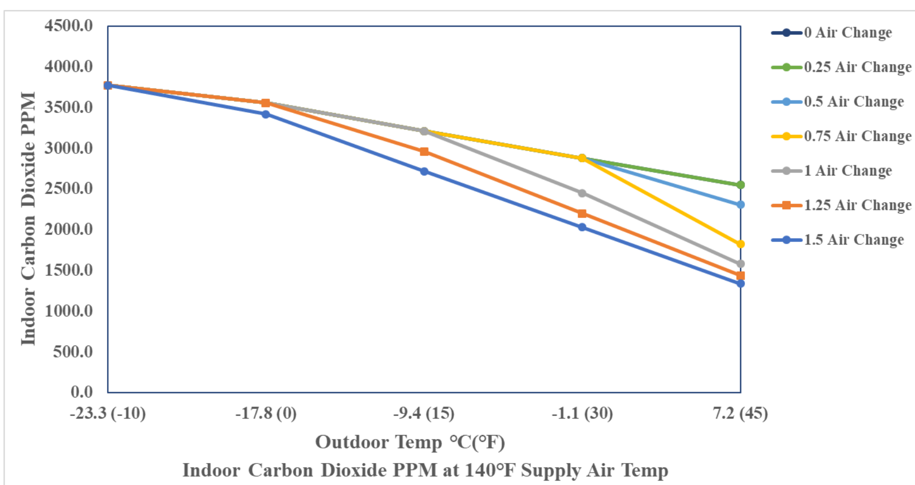


Fig. 5.14. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature at 140°F supply air temperature.

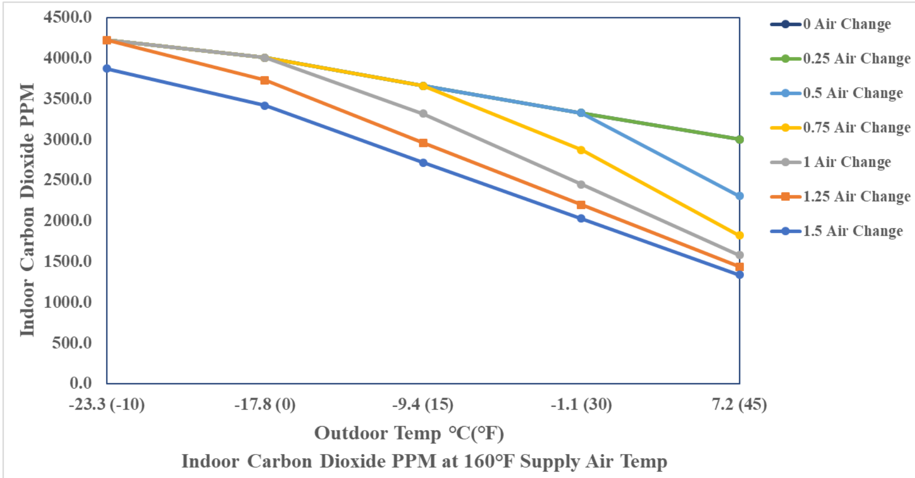


Fig. 5.15. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature at 160˚F supply air temperature.

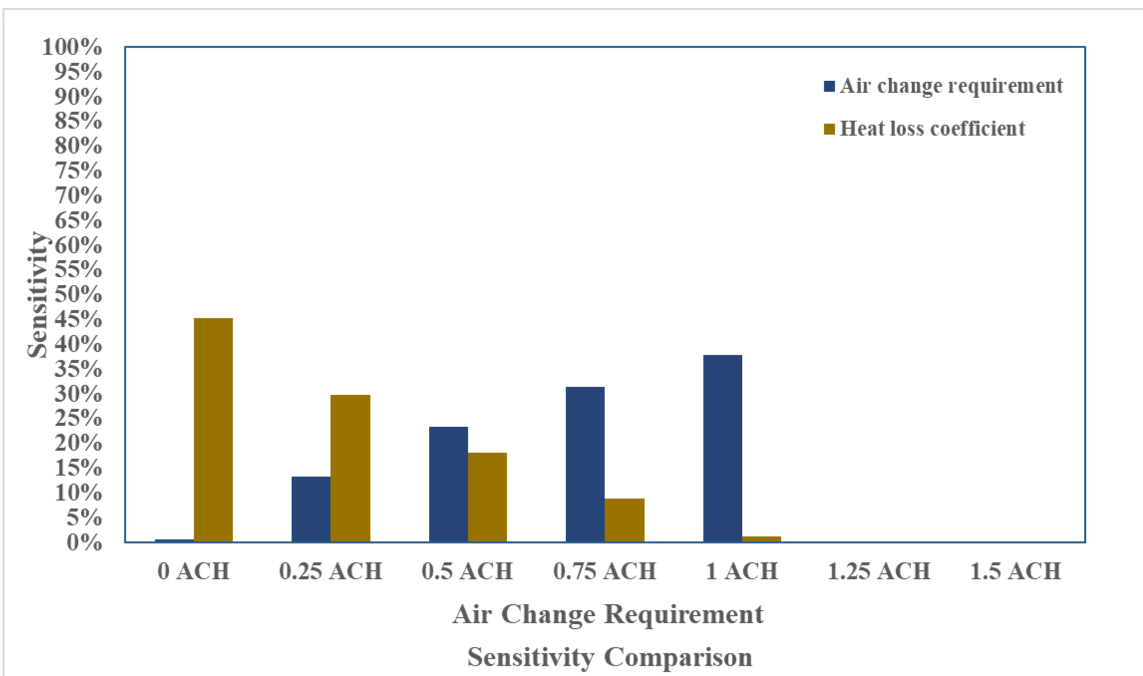


Fig. 5.16. Sensitivity comparison (constant air flow rate).

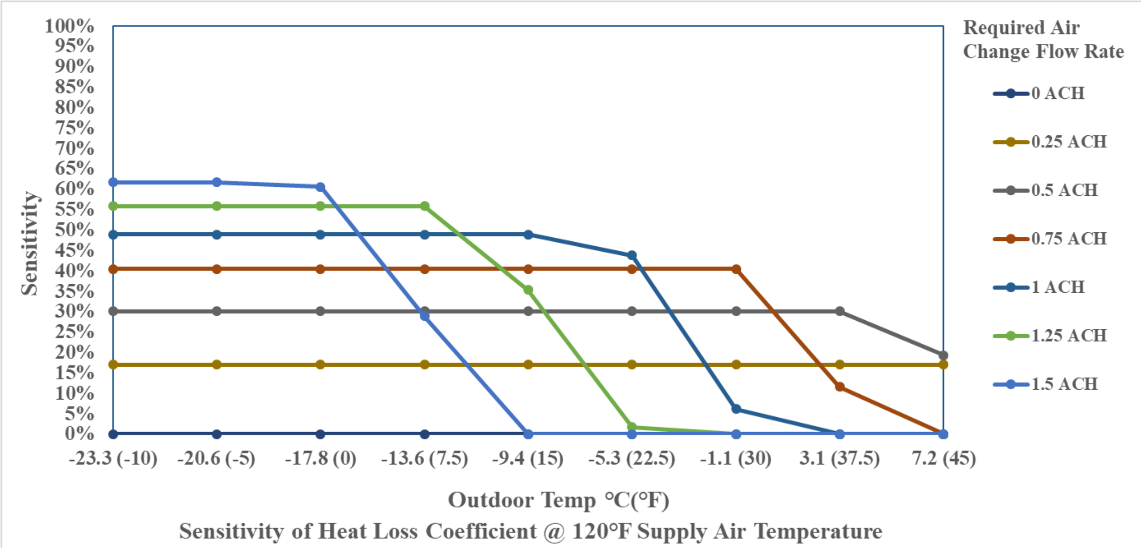


Fig. 5.17. Sensitivity of heat loss coefficient at 120°F supply air temperature.

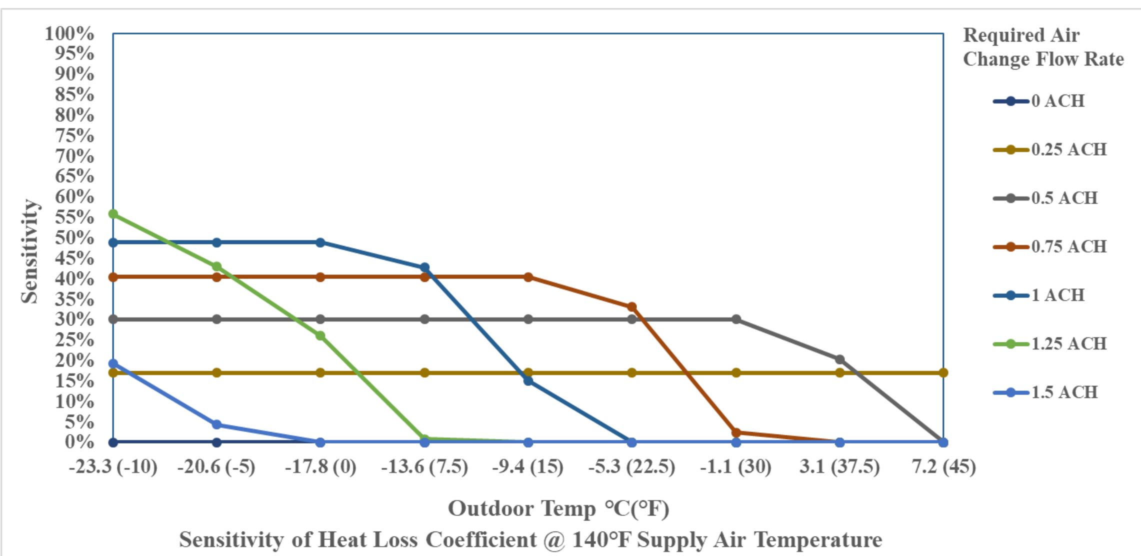


Fig. 5.18. Sensitivity of heat loss coefficient at 140°F supply air temperature.

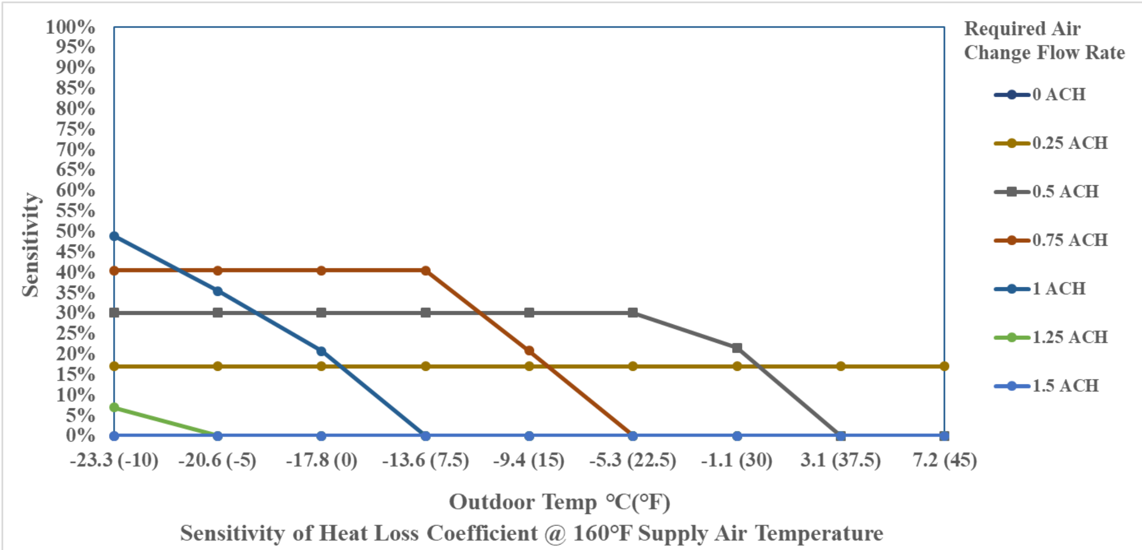


Fig. 5.19. Sensitivity of heat loss coefficient at 160°F supply air temperature.

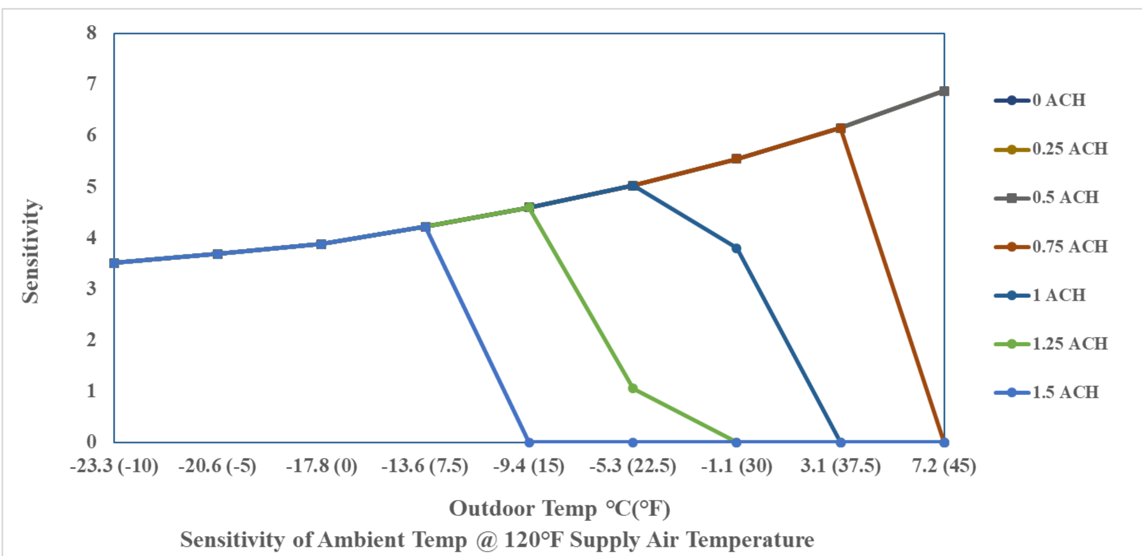


Fig. 5.20. Sensitivity of ambient temp at 120°F supply air temperature.

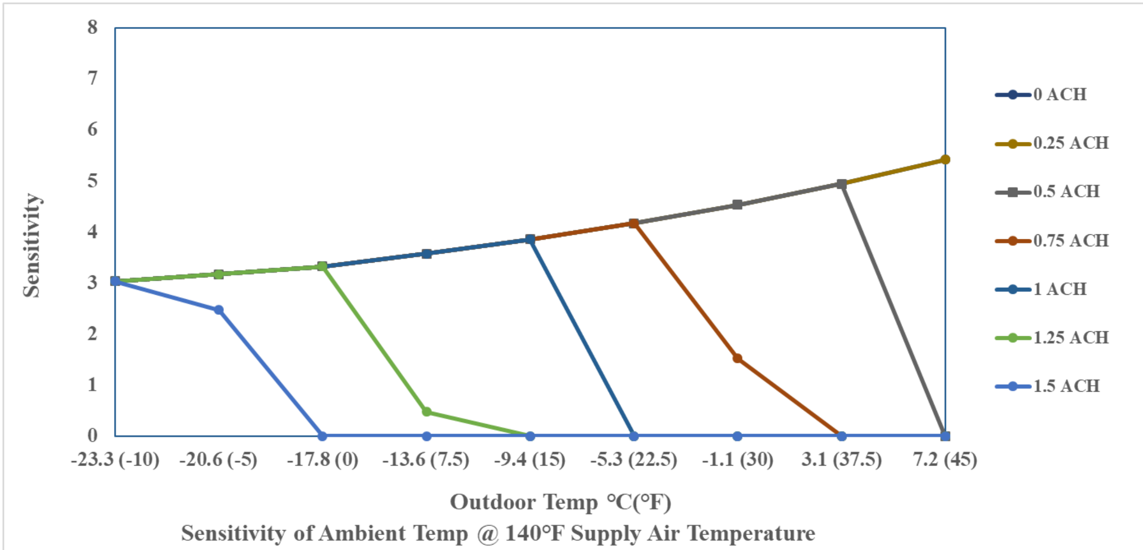


Fig. 5.21. Sensitivity of ambient temp at 140°F supply air temperature.

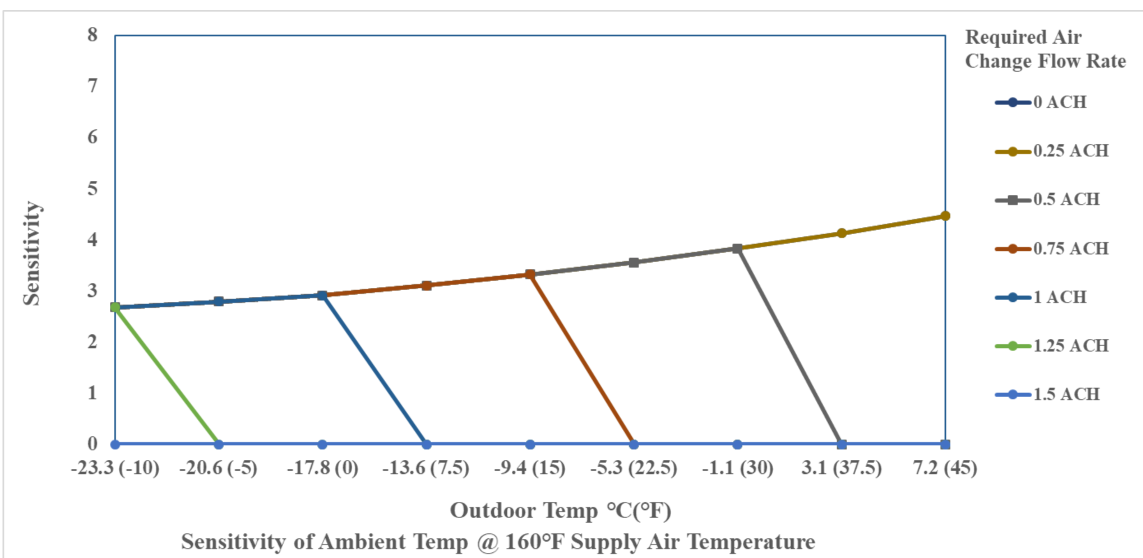


Fig. 5.22. Sensitivity of ambient temp at 160°F supply air temperature.

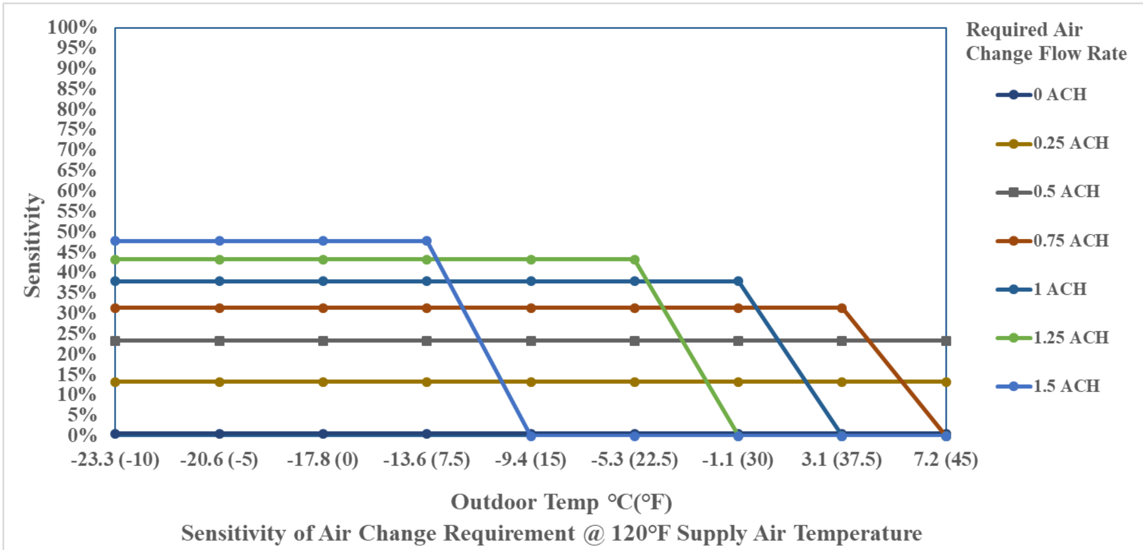


Fig. 5.23. Sensitivity of air change requirement at 120°F supply air temperature.

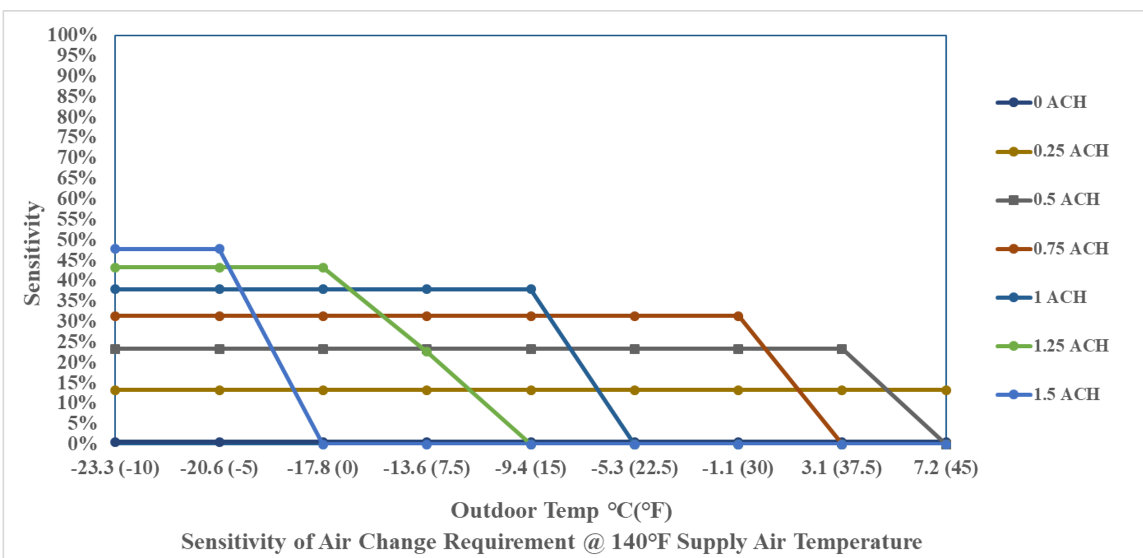


Fig. 5.24. Sensitivity of air change requirement at 140°F supply air temperature.

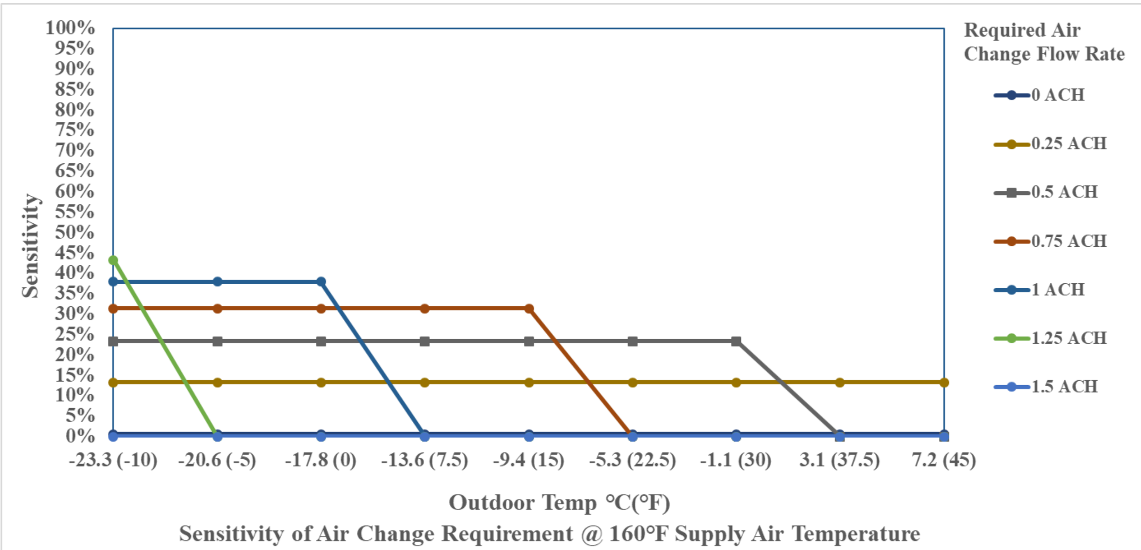


Fig. 5.25. Sensitivity of air change requirement at 160°F supply air temperature.

6. CONCLUSION

Research and studies are conducted based on the objectives.

1. Systematic energy efficiency has been defined and used to evaluate the overall performance of the space heating system.

2. Heating system performance indicators and input parameters which will affect the indicators are studied and determined. Indicators include systematic energy efficiency, exergy efficiency and carbon dioxide concentration level. Input parameters include heat loss coefficient of the building, ambient temperature and air change requirement of the space.

3. Methodology of each calculation model is studied and created.

4. System performance indicators studies and results:

   - Systematic energy efficiency: In the case introduced in this research, indirect fired heating system always has a constant systematic energy efficiency which is 80%, the same as the heaters device efficiency. For direct fired heating system, systematic energy efficiency is not always constant. Input parameters such as control method (constant air flow rate or constant supply air temperature), outdoor ambient temperature, air change rate and heat loss coefficient of the building envelope will impact the systematic energy efficiency. The systematic energy efficiency varies from 40% to 92% under different condition. The highest systematic energy efficiency is 92% which is the device efficiency of the heater. The results show that this systematic energy efficiency is necessary while evaluating the overall performance of the heating system considering device impact to the system, because the device efficiency of the heater is always constant that it can not be used to represent the system efficiency under all kinds of conditions.

- Systematic exergy efficiency: The systematic exergy efficiencies for both systems are very low (below 10%) because of the function of heating system. In a heating system, high quality energy source (fossil fuel) is used to provide heat which is low quality energy and exergy is destroyed when the heat is transferred through boundary. Systematic exergy efficiency of indirect fired heating system (4%-10%) is relatively higher than direct fired heating system (1%-4%) because of the high temperature exhaust air from heater. Exergy efficiency doesn't describe how much and how well energy is used in a heating system because output of this heating system might not be a useful output. It only shows the opportunity that waste heat can be reclaimed. The higher the systematic exergy efficiency is, the higher possibility that waste heat can be used. Systematic exergy efficiency can be used as a backup in this heating system for optimizing purpose.

- Carbon dioxide concentration level: The carbon dioxide concentration level of direct fired heating system varies from 1000 to 4500 PPM under different conditions. Indoor carbon dioxide PPM will increase due to combustion of natural gas. While using direct fired heating system, indoor air quality should be concerned. More fresh air might be needed to keep the indoor carbon dioxide PPM under critical level.

5. Sensitivity analysis of input parameters shows that for direct fired heating system, sensitivity of input parameters (heat loss coefficient, ambient temperature and air change requirement) will vary under different conditions.

Based on the results and conclusion of this research, it is known that direct fired heaters dont always have higher systematic energy efficiency even though typically they have higher device efficiency compared to indirect fired heaters. Extra fresh air brought into the building space by direct fired heaters is the reason of this. Systematic energy efficiency introduced in this research provides a way to evaluate the heating system performance considering not only the heating device but also the whole system. Carbon dioxide concentration level (indoor air quality) is also a concern when using direct fired heaters. Extra amount of fresh air might be needed to keep the carbon dioxide level under comfort level because the combustion of direct fired heaters will generate more carbon dioxide in the space.

7. FUTURE WORK

1. For the systematic energy efficiency study, case study by collecting and analyzing data needs to be done to validate the conclusion that systematic energy efficiency of direct fired heating system will vary under different ambient temperature and air change requirement.

2. Study the inflection point mentioned in section 5.1.1 as different ratios of building loss to ventilation loss.

3. While analyzing the systematic energy efficiency of direct fired heating system in this research, it's separated from carbon dioxide concentration level study. Considering control the carbon dioxide concentration below a certain level, the systematic energy efficiency of direct fired heating system could be different (lower than current results would be expected). Further studies can be done to evaluate the systematic energy efficiency of direct fired heating system while controlling the carbon dioxide level at the same time.

4. In this research, we only consider carbon dioxide for indoor air quality. Other pollutants such as carbon monoxide needs to be concerned when using direct fired heaters.

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