SYSTEMATIC ENERGY AND EXERGY EFFICIENCY STUDY FOR DIRECT AND INDIRECT FIRED HEATERS

By

Bin Wang

A research study project related to system modeling and comparison in systematic energy and exergy efficiency between indirect and direct fired space heating equipment being prepared for the fulfillment of requirements for the degree of Master of Science in Mechanical Engineering In the School of Engineering and Technology At Indiana University Purdue University Indianapolis (IUPUI)

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Adviser

Dr. Ali Razban, PhD, PE, MBA, CEM, CP EnMS

Director, Bachelor of Science in Energy Engineering Program

Assistant Director, DOE Industrial Assessment Center

Clinical Associate Professor,

Department of Mechanical and Energy Engineering

Purdue School of Engineering and Technology

Indiana University Purdue University Indianapolis (IUPUI)

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1. Introduction

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 useable 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 instance, HTHV direct fired heating equipment is generally recognized to have a thermal efficiency of 92% when simple input/output efficiency is used. This energy efficiency is considered higher than indirect fired heater. But in order to maintain the air quality of indoor space, extra fresh air need to be brought into the space. Under low ambient air temperature condition, extra fresh air intake will result in higher heating load to heat the low temperature air up to required indoor temperature. In this case, the simple heater device efficiency will not be enough to evaluate the overall system efficiency. Besides, the current AFUE method calculates only the energy efficiency which is thermodynamics first law efficiency.

Application of exergy principle becomes more and more widely used because it considers how different levels of energy are used, in other words, how energy activities affect the entropy generation of the whole universe. In this report, 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 in Simulink have been built to calculate the systematic energy and exergy efficiency, and to evaluate the systematic energy and exergy efficiency of heating systems with two different types of heaters, direct fired and indirect fired heaters. Two scenarios are considered for the direct fired heating system, constant supply air flow rate and constant supply air temperature. These scenarios represent two different types of control which might be used for direct fired heaters. In both scenarios, the systematic energy efficiencies of direct fired heater are not always constant at its device efficiency but related to several parameters such as space air change requirement and ambient temperature.

For indirect fired heaters, combustion is totally isolated from supply air flow. 100% return air is used for the heater itself. The combustion won't 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. Methodology

2.1. Thermodynamics model for energy and exergy study

General equations of mass, energy and exergy balances are applied considering steady state conditions to the system. Changes in kinetic and potential energy are negligible.

2.1.1. 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.

2.1.1.1. Energy balance

Energy balance equation of a control volume can be expressed by equation 1 according to the first law of thermodynamics [1]:

$$\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W} + \sum_i \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e \right) \quad (1)$$

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

2.1.1.2. Systematic energy efficiency

In a commercial or industrial space which needs to be heated, the inner space is always maintained at a higher temperature than outdoor environment. So the heat is continuously being lost through the boundary. Building codes, such as ASHRAE Standard 62.1 [2], require that during periods when the building is occupied by people, an essential amount of outside fresh air is required to replace indoor air which 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 2 and 3:

$$\eta_{SYS} = \frac{Heating\ Load}{NG\ Consumption\ in\ terms\ of\ Btu} \quad (2)$$

$$Heating\ Load = Heat\ Loss\ Thru\ Boundary + Heat\ Loss\ via\ Essential\ Air\ Change \quad (3)$$

According to ASHRAE Standard 62.1, the fresh air flow required for a building is related to several parameters including zone flow area and maximum zone population [2]. When the zone population is very low (no people or few people working in this space such as warehouse), the required fresh air flow could be low. Sometimes the direct fired heater will bring in more fresh air than that is needed to satisfy the code requirement for fresh air. The exceeding portion of the fresh air over essential air change is considered as unnecessary and will result in more energy consumption.

2.1.2. 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, the dead state is the outdoor air state. So the temperature of the dead state is the same as outdoor air temperature (To), and the pressure of the dead state is assumed to remain at 100 kPa (Po).

2.1.2.1. Exergy balance

The general exergy balance applied to a control volume is expressed by equation 4 [1]:

$$\frac{dEx_{CV}}{dt} = \sum_j \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_J - \left(\dot{W}_{CV} - p_o\frac{dV_{CV}}{dt}\right) + \sum_i \dot{m}_i ex_i - \sum_i \dot{m}_e ex_e - \dot{Ex}_D \tag{4}$$

2.1.2.2. Exergy calculation

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

$$ex = ex^{ch} + ex^{tm} \tag{5}$$

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:

$$ex^{tm} = h - h_o - T_o(s - s_o) \tag{6}$$

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:

$$\overline{ex}^{ch} = \sum_i y_i \overline{ex}_i^{ch,o} + \bar{R}T_o \sum_i y_i ln(y_i) \tag{7}$$

where $\overline{ex}_i^{ch,o}$ is the standard chemical exergy [3,4]; y_i is the molar fraction of each species. The standard chemical exergy can be found in source [5].

The specific chemical exergy can be calculated by equation 8,

$$ex^{ch} = \frac{\overline{ex}^{ch}}{M} \tag{8}$$

where *M* is the molar mass of flow.

2.1.2.2. 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 4 can be simplified to equation 9:

$$\sum_i \dot{m}_i ex_i = -\sum_j \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_J + \sum_i \dot{m}_e ex_e + \dot{Ex}_D \tag{9}$$

Exergy efficiency [6] is defined as equation 10:

$$\varepsilon = \frac{Ex_{out}}{Ex_{in}} = \frac{\sum_i \dot{m}_e ex_e}{\sum_i \dot{m}_i ex_i} \quad (10)$$

2.2. 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. This point of concentration is what needs to be concerned. In this research, only final steady carbon dioxide concentration level is considered. In order to study the impact of direct fired heater towards the indoor air quality, carbon dioxide generated by human and other process inside the building is not considered.

2.2.1. Carbon dioxide balance

Parts per Million (PPM) is normally used to indicate the carbon dioxide concentration. PPM is defined as volumetric percentage [6]. At 1atm pressure, we can assume the air is ideal gas. For ideal gas, molecular percentage is equal to volume percentage. Carbon dioxide molecular percentage in the atmosphere is very low (0.04%), the change of carbon dioxide PPM has very limited impact on the density of the air. So, we can assume that carbon dioxide PPM change of air won't affect air density.

Also, we assume the natural gas consists of 95% of CH_4, 3% of C_2H_6 and 2% of N_2 in mole since other components in natural gas are very minimum [7]. Table 1 shows the component molecular percentage and net heat value (NHV) [8] of each component. Assume N_2 won't participate in reaction during combustion, so there is no heat value of N_2.

Table 1. 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

The molar mass of natural gas can be calculated by equation 11.

$$M_{NG} = 95\% M_{\mathrm{CH4}} + 3\% M_{\mathrm{C2H6}} + 2\% M_{\mathrm{N2}} = 0.01666\ kg/mol \quad (11)$$

Where,
M_{NG} is molar mass of natural gas
M_{CH4} is molar mass of CH_4, 0.016 kg/mol
M_{C2H6} is molar mass of C_2H_6, 0.030 kg/mol
M_{N2} is molar mass of N_2, 0.028 kg/mol

The net heat value of natural gas can be calculated by equation 12.

$$NHV_{NG} = \frac{95\% M_{\mathrm{CH4}} NHV_{\mathrm{CH4}} + 3\% M_{\mathrm{C2H6}} NHV_{\mathrm{C2H6}}}{M_{NG}} = 48{,}034\ kJ/kg \tag{12}$$

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 13.

$$\dot{M_{com}} = \frac{Natural\ Gas\ Input}{NHV_{NG} M_{NG}} (95\% \times 1 + 3\% \times 2) \tag{13}$$

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

Carbon dioxide concentration balance in a certain space can be presented by equation 14.

$$\frac{\dot{m}_s PPM_{atm}}{M_{air}} + \frac{\dot{m_{AC}} PPM_{atm}}{M_{air}} + \dot{M_{com}} = \frac{\dot{m_{exf}} PPM}{M_{air}} \tag{14}$$

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

$$\dot{m}_s + \dot{m_{AC}} + \frac{Natural\ Gas\ Input}{NHV_{NG}} = \dot{m_{exf}} \tag{15}$$

Based on equation 14 and 15, we calculate the carbon dioxide concentration in the space in PPM.

2.3. Sensitivity analysis

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

Sensitivity analysis is used to determine how 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 [9].

2.3.1. Measurement of sensitivity analysis

Following steps are used to conduct sensitivity analysis [9]:

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.

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.

3. System model

3.1. Systematic energy and exergy modelling

Simulink is used to model and simulate the indirect and direct fired heating system based on thermodynamics models. The schematic diagrams of indirect fired and direct fired heating system are shown in Figure 1 and Figure 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 (9). In indirect fired heating system, the space is considered to be at atmospheric pressure. Infiltration should be considered for this type of system [10]. 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.

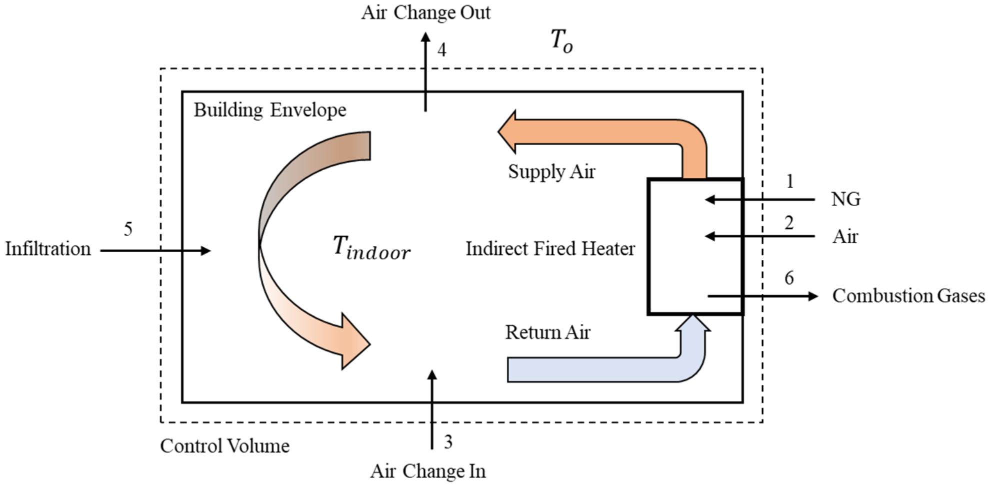


Figure 1. Schematic diagram of indirect fired space heating system.

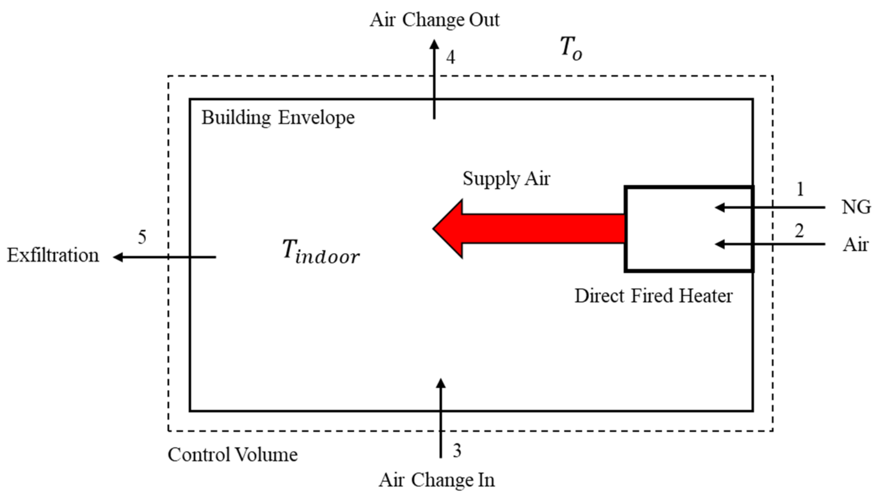


Figure 2. Schematic diagram of direct fired space heating system.

3.2. Carbon dioxide concentration level modelling

The carbon dioxide concentration level model is created based on the methodology in section 2.2. 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 [11].

3.3. Example system setup

A 10,000 ft^2, 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. Assuming the warehouse is rarely occupied by human. Without any special requirement, air change requirement will be fine to set of a range from 0 ACH to 1.5 ACH [12]. The device efficiency of indirect and direct fired heater is 80% and 92% respectively [13]. Direct fired heater fresh air volume flow rate is 3,500 CFM according to a proper heater selection for the system [14].
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 2 [7].

Table 2. 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		

3.4. Assumptions

The following assumptions were made during the calculation in order to simplify the analysis and comparison.

3.4.1. General

- The temperature and pressure of supply NG is set close to ambient temperature and pressure. The thermomechanical exergy of NG is also negligible.

3.4.2. Indirect fired heating system

- 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.
- The exhaust temperature of indirect fired heater combustion gas is maintained at 182°C (360°F) [15].
- 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 [16].

3.4.3. Direct fired heating system

- Fresh air intake for direct fired heater can be considered as effective air change.
- Constant air flow rate and constant supply air temperature.

3.4.4. Carbon dioxide concentration level

- The heating system is a steady system.
- Air is ideal gas.
- Carbon dioxide PPM change of air won’t affect air density.

4. Results and discussion

4.1. Systematic energy efficiency (Constant air flow rate for direct fired heater)

4.1.1. Systematic energy efficiency

The systematic energy efficiency calculation results for ambient temperature range of -20 to 10°C and air change per hour of 0 to 1.5 are shown in Figure 3. 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 systematic energy efficiency doesn't change while ambient temperature varies, we need to refer to the definition of systematic energy efficiency by equation (1) 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 ambient temperature. According to energy balance, NG input in terms of the rate of energy in kW (Btu/h) should be equal to total heat rate delivered out of the boundary divided by heater device efficiency, it's also a function of ΔT. So the impact of ΔT is cancelled when calculate the fraction.

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.

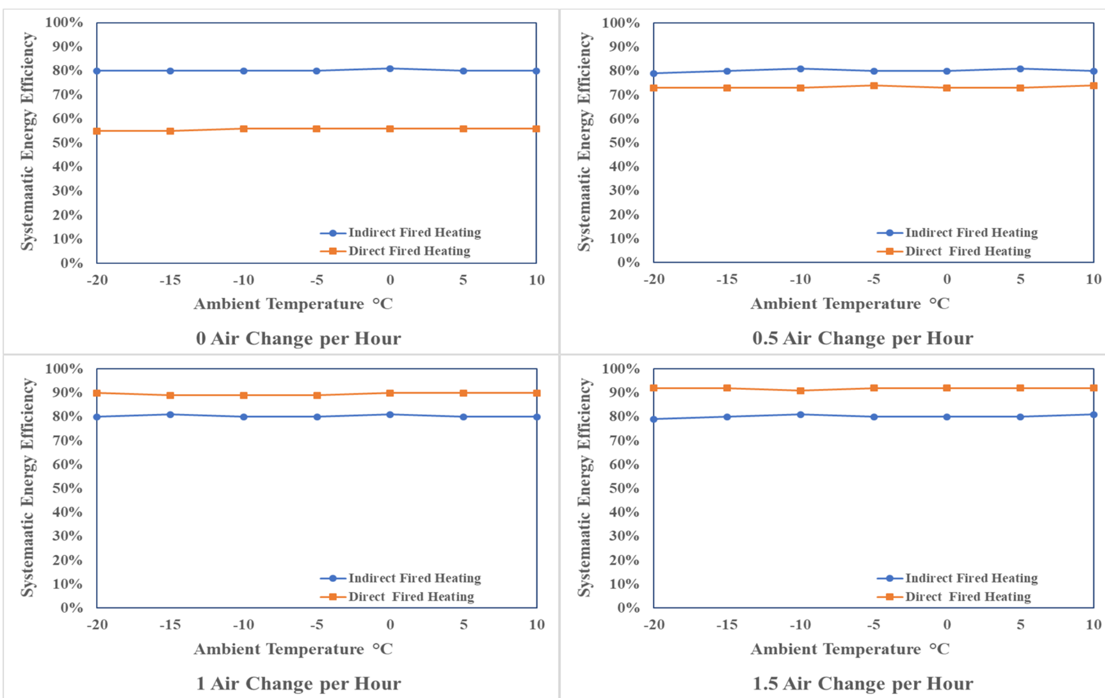


Figure 3. Systematic energy efficiency vs. outdoor temperature under different air change requirement

Figure 4 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.

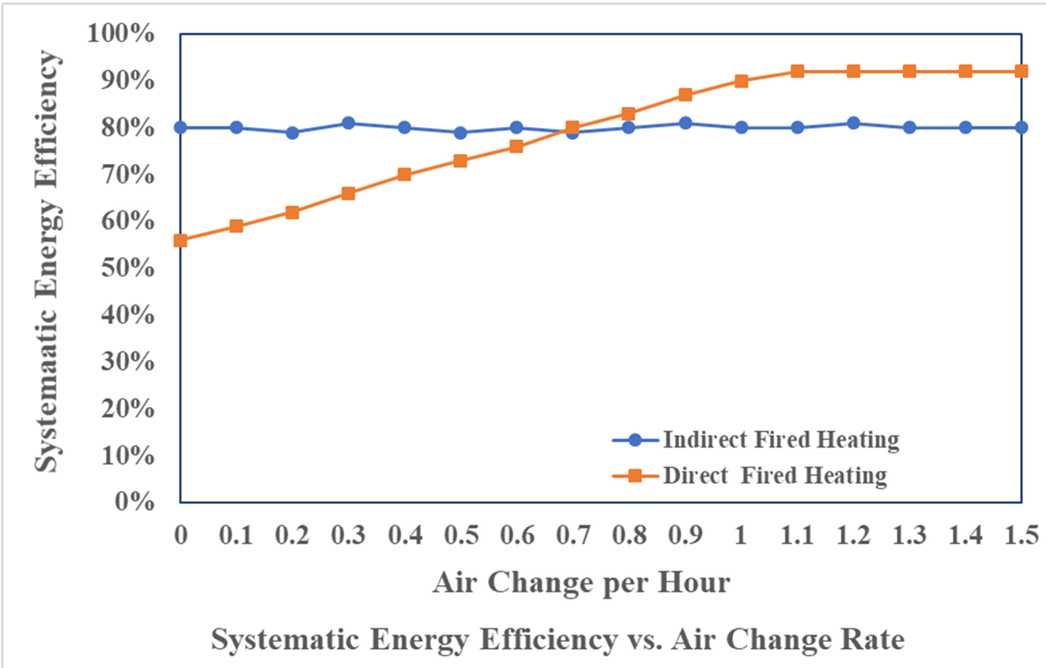


Figure 4. Systematic energy efficiency vs. air change requirement

4.1.2. Natural gas demand

Figure 5 show the natural gas demand comparison between indirect and direct fired heating system in the constant air flow rate scenario. Natural gas demands of indirect and direct fired heating system are related to both 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 below the inflection point which is mentioned in subsection 4.1.1. Above this point, natural gas demand will increase as air change requirement increases.

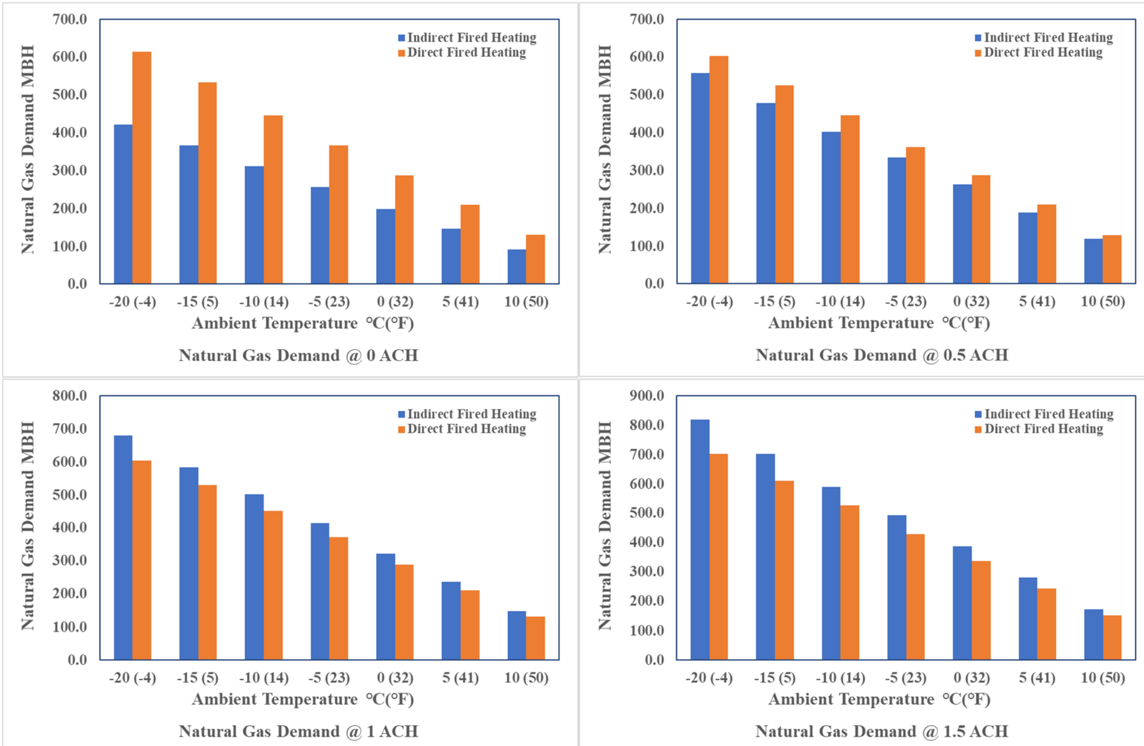


Figure 5. Natural gas demand vs. outdoor temperature under different air change requirement

4.2. Systematic energy efficiency (Constant supply air temperature for direct fired heater)

4.2.1. 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 3a, 3b, 3c and Figure 6. For initial comparison purposes, the calculation results done by Thermo-Cycler are also included.

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.

The results calculated by the model under 0 air change condition are very close to the Thermo-Cycler calculation results.

Table 3a. Systematic energy efficiency of direct fired heating system at 160°F supply air temperature at variable air change

	Ambient T °C (°F)

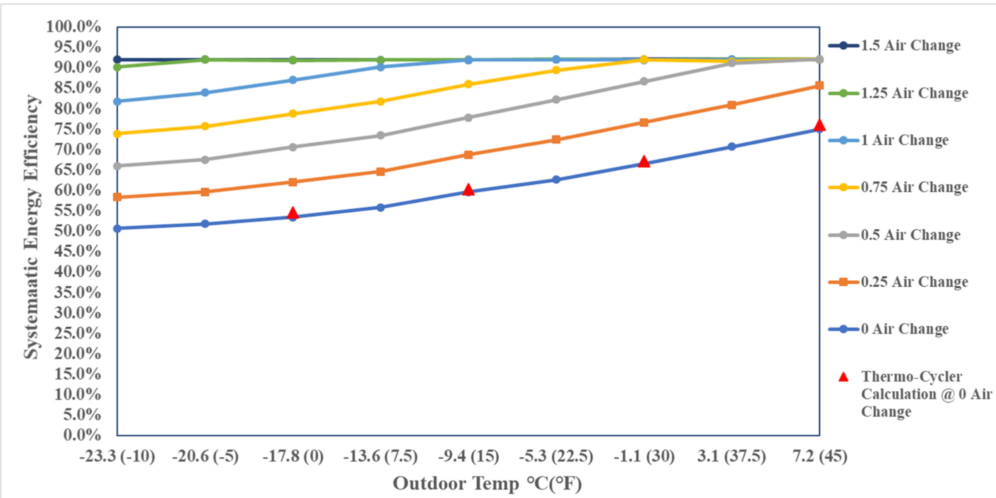
160°F Supply T	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	50.7%	51.8%	53.4%	55.8%	59.6%	62.6%	66.6%	70.7%	75.0%
0.25 Air Change	58.4%	59.7%	62.0%	64.6%	68.7%	72.4%	76.7%	80.9%	85.6%
0.5 Air Change	66.0%	67.5%	70.6%	73.4%	77.8%	82.2%	86.7%	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%
Thermo-Cycler Calculation @ 0 Air Change			54.6%		60.3%		67.2%		76.0%

Table 3b. 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 3c. 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%



Systematic Energy Efficiency at 160°F Supply Air Temp

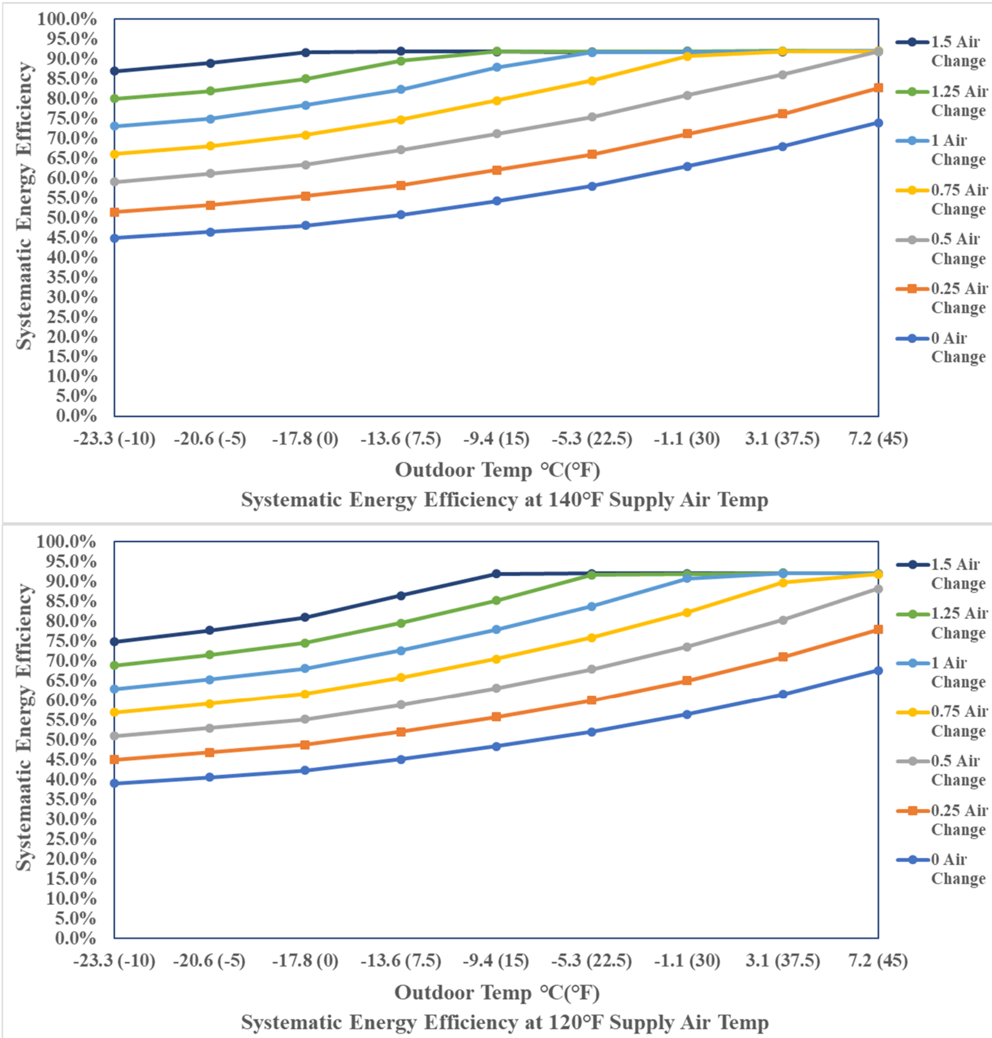


Figure 6. Systematic energy efficiency for direct fired heating system vs. outdoor air temperature under different air change requirement at different supply air temp

Figure 7 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.

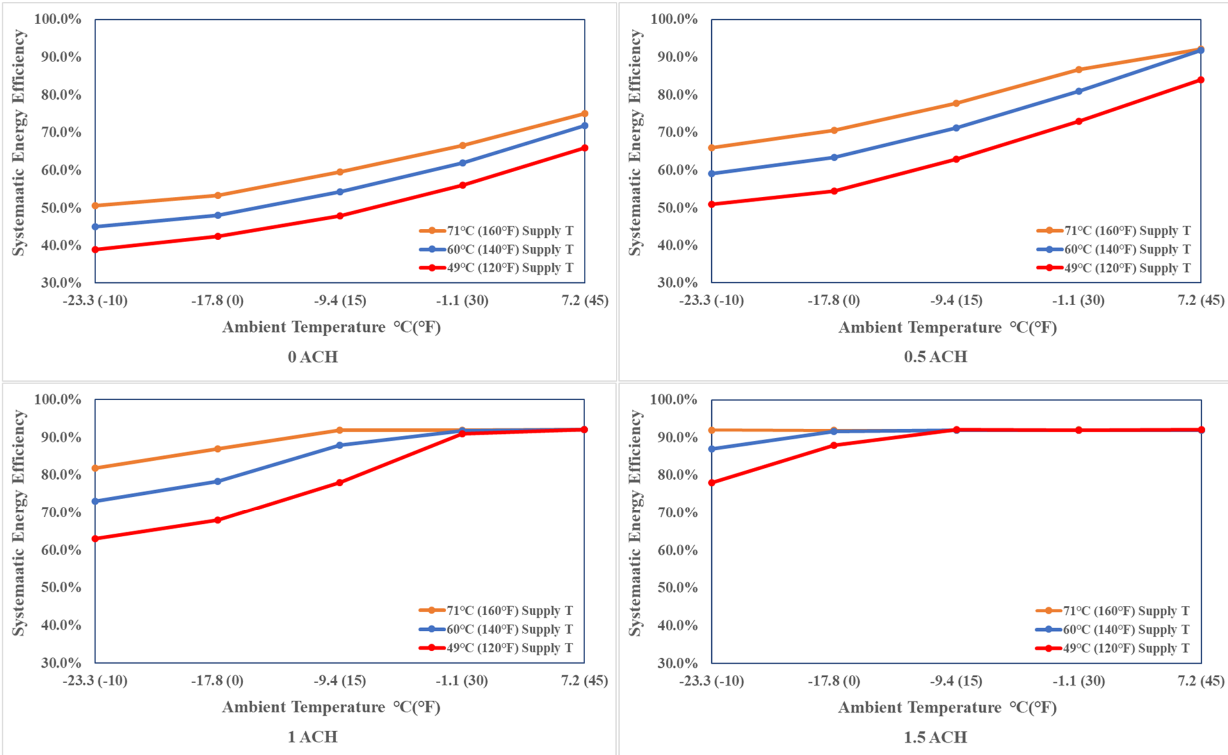


Figure 7. Systematic energy efficiency for direct fired heating system vs. outdoor air temperature under different supply air temperature

Figure 8 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.

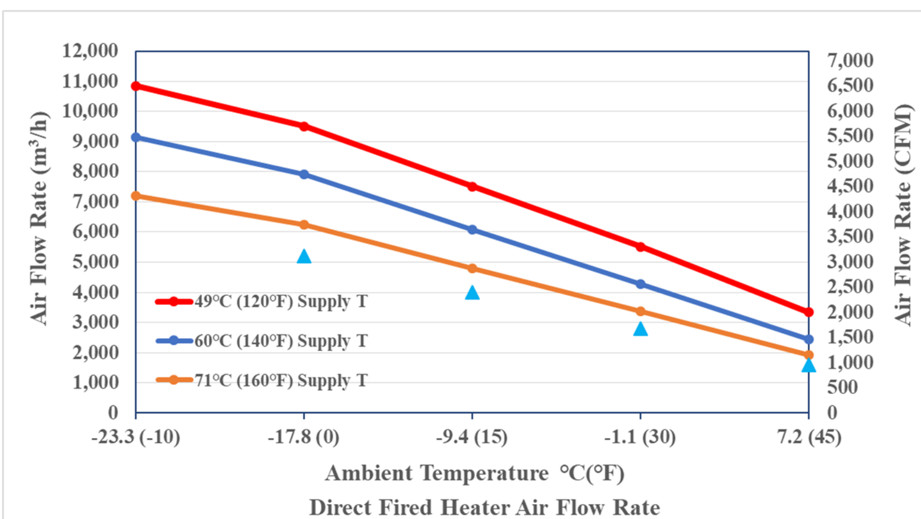


Figure 8. Direct fired heater air flow rate vs. outdoor air temperature

4.2.2. Natural gas demand

The natural gas demand of indirect fired heating system is shown in Table 4a, while natural gas demand of direct fired heating system at certain supply air temperature are shown in Table 4b, 4c and 4d, respectively. Figure 9 and 10 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, the natural gas demand will increase. Supply air flow rate is related to supply air temperature, ambient temperature and air change requirement.

Table 4a. 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 4b. Natural gas demand of direct fired heating system at 160°F supply air temperature at variable air change

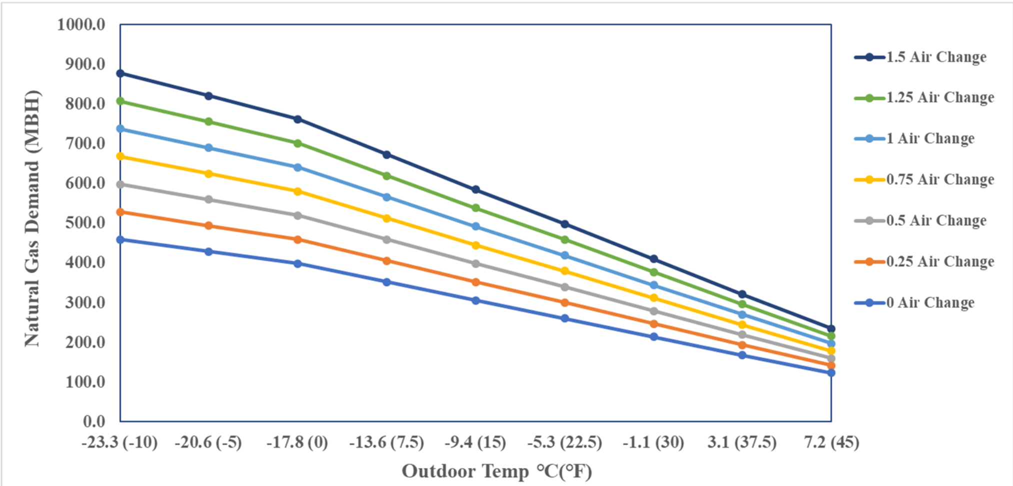
NG Demand of Direct Fired Heating@160°F Supply T (MBH)	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 Air Change	713.7	648.3	583.3	491.1	405.3	327.8	254.7	188.0	129.1
0.25 Air Change	713.7	648.3	583.3	491.1	405.3	327.8	254.7	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 4c. Natural gas demand of direct fired heating system at 140℉ supply air temperature at variable air change

NG Demand of Direct Fired Heating@140°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 4d. Natural gas demand of direct fired heating system at 120℉ supply air temperature at variable air change

NG Demand of Direct Fired Heating@120°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



Natural Gas Demand of Indirect Fired Heating

Figure 9. Natural gas demand for indirect fired heating system vs. outdoor air temperature under different air change requirement

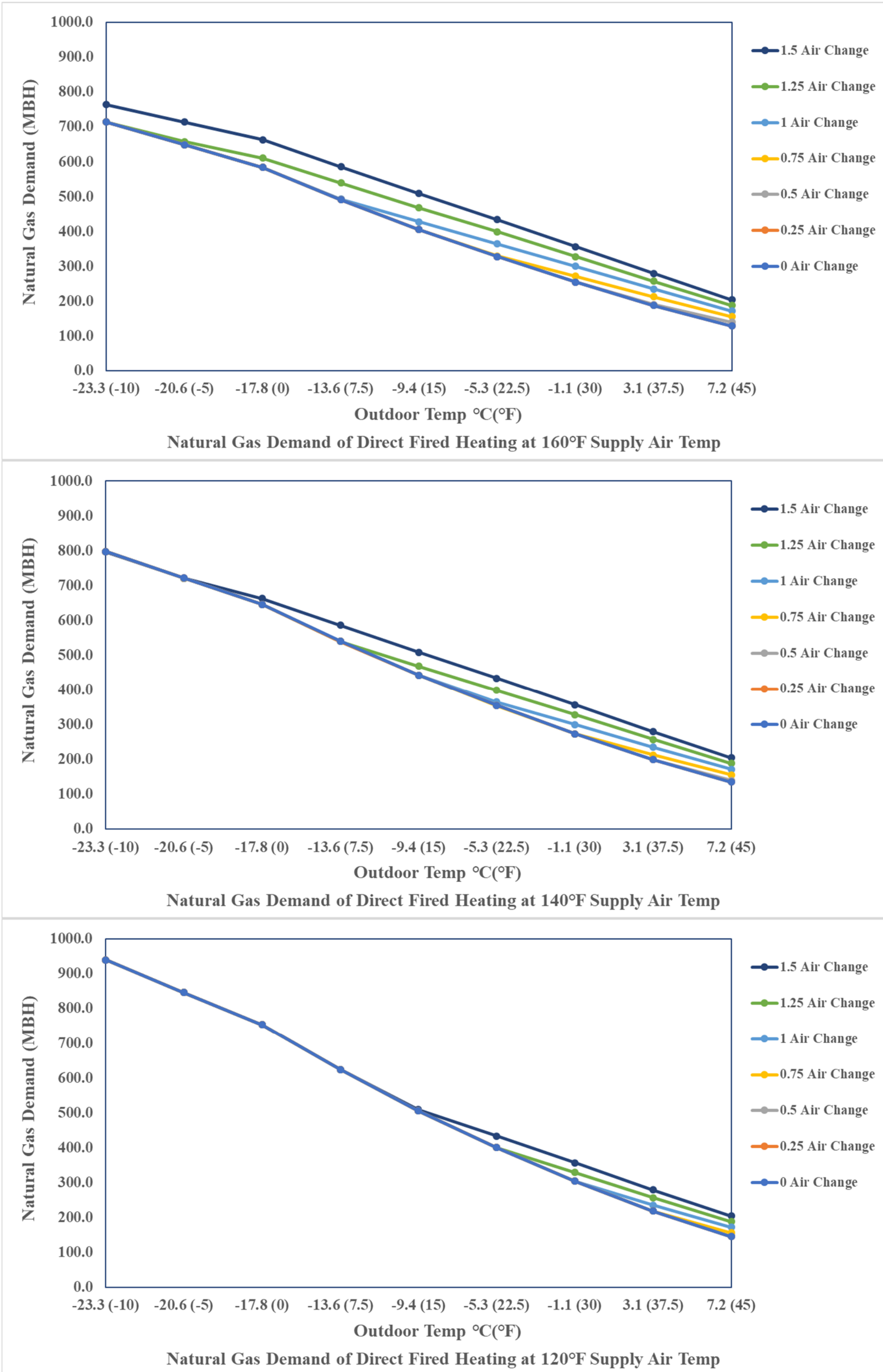
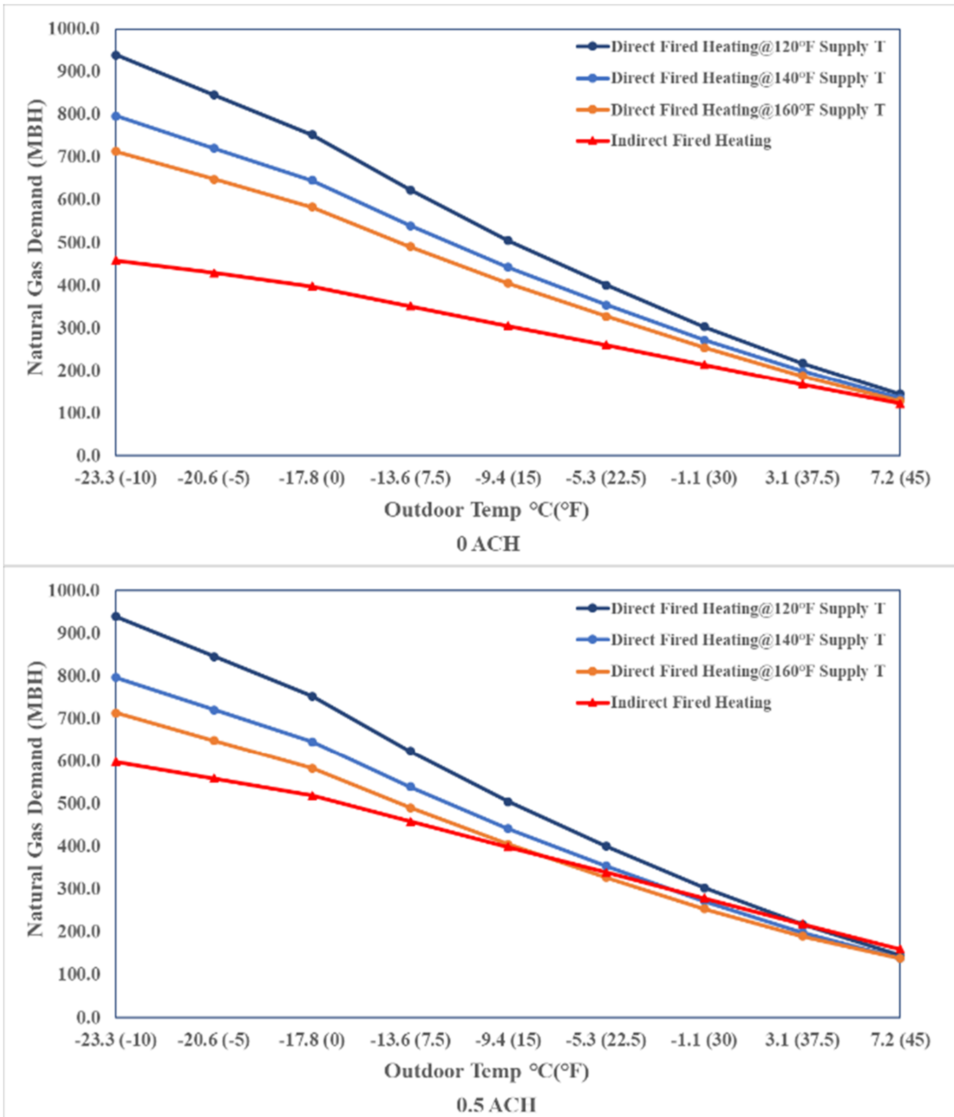


Figure 10. Natural gas demand for direct fired heating system vs. outdoor air temperature under different air change requirement (160℉/140℉/120℉ supply air temp)

Figure 11 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.



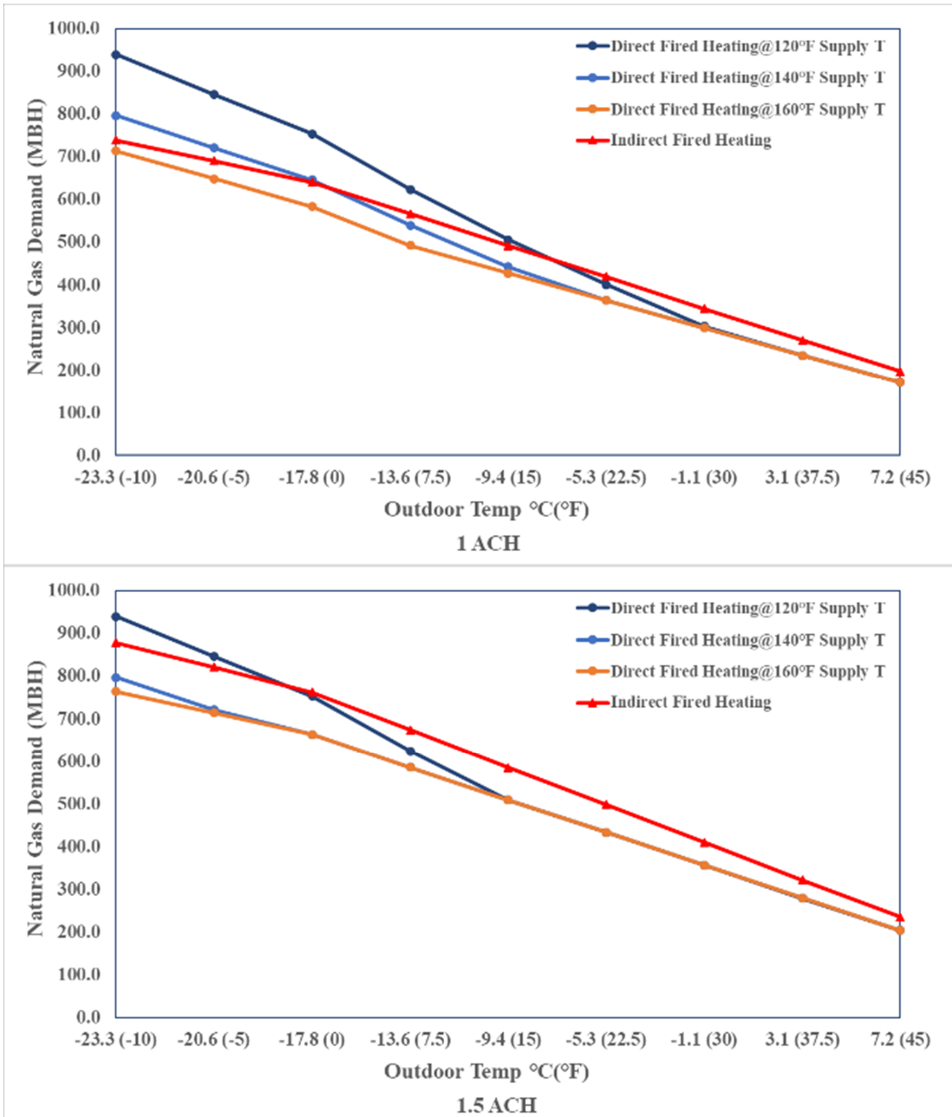


Figure 11. Natural gas demand comparison between direct fired heating system

4.3. Exergy efficiency

4.3.1. Systematic exergy efficiency

The systematic exergy efficiency calculation results under different ambient temperature and required air change per hour are shown in Figure 12. 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. It’s 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.

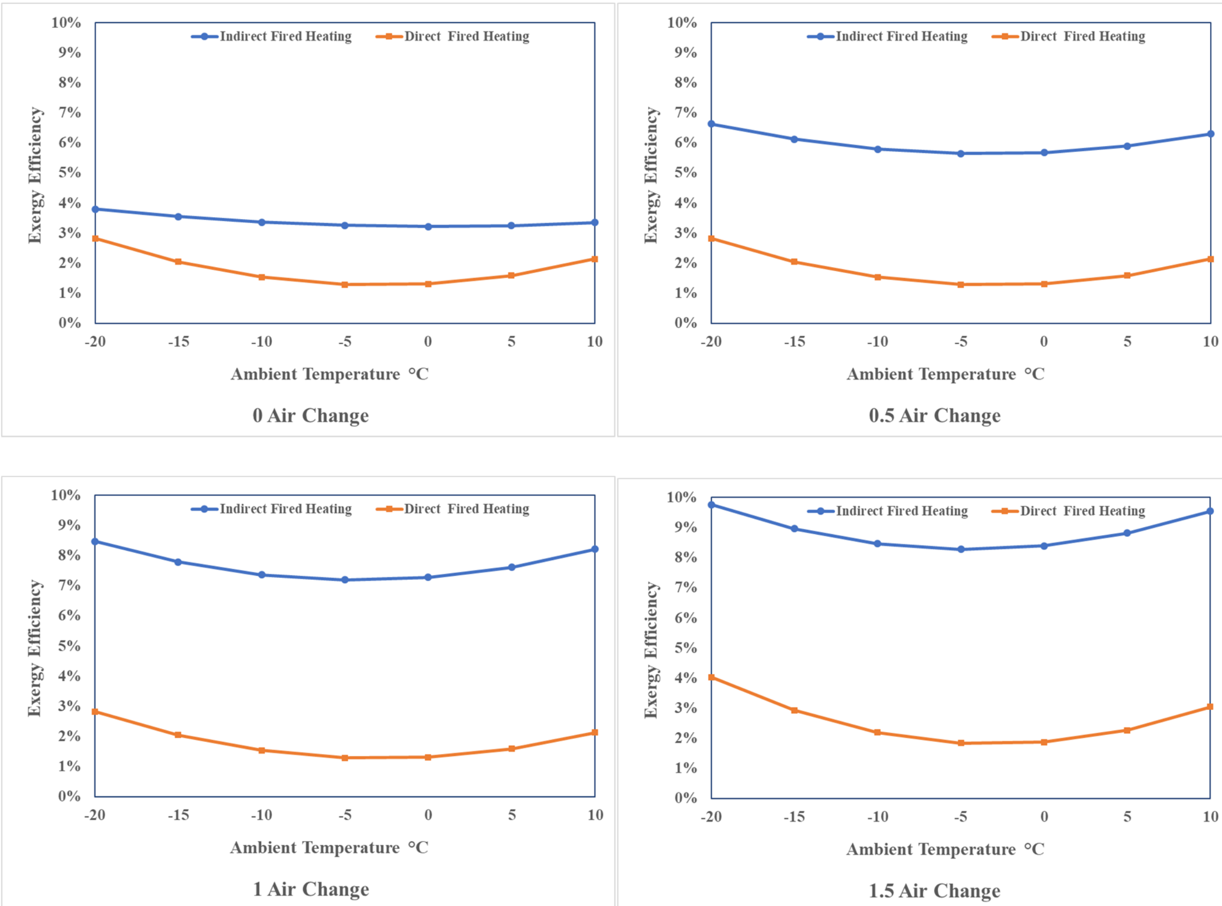


Figure 12. Systematic exergy efficiency.

4.3.2. 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℃ (65°F) indoor space temperature. For direct fired heater, variable ambient temperature and supply air temperature were applied to the calculation. Figure 13 shows the results of single heater exergy efficiency for both heaters.

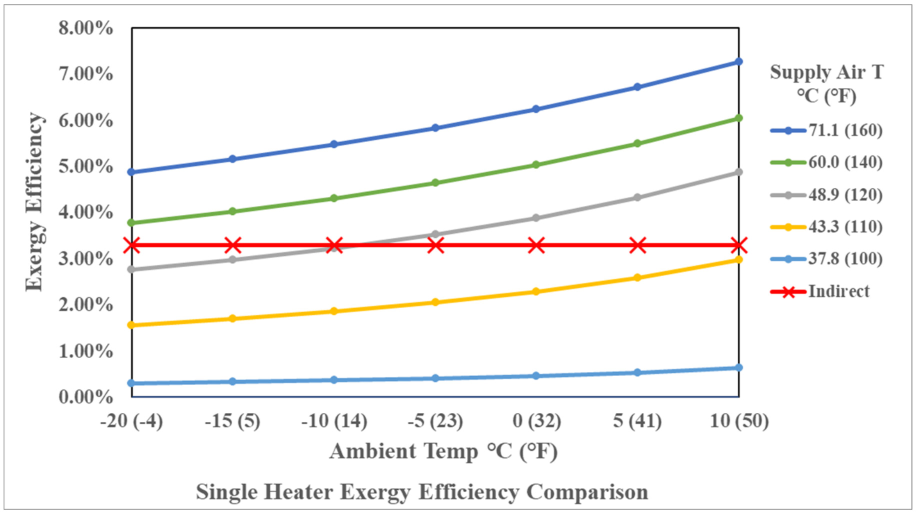


Figure 13. Single heater exergy efficiency.

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 friction 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.

4.4. 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 won't be affected by heating devices since combustion of indirect fired heaters is isolated from indoor return air.

4.4.1. 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 and Figure 14 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.

Table 5. Indoor carbon dioxide PPM under different air change requirement and ambient temperature.

CO2 (PPM)		Outdoor Temperature °C (°F)						
		-20 (-4)	-15 (5)	-10 (14)	-5 (23)	0 (32)	5 (41)	10 (50)
		-20	-15	-10	-5	0	5	10
0 Air Change	**Direct Fired Heating**	4392.5	3874.4	3303.6	2794.2	2284.5	1774.5	1264.2
0.5 Air Change	**Direct Fired Heating**	4324.8	3815.6	3306.0	2764.0	2286.0	1775.6	1253.4
1 Air Change	**Direct Fired Heating**	4326.9	3855.5	3340.0	2824.2	2287.0	1776.3	1265.3
1.5 Air Change	**Direct Fired Heating**	3599.8	3184.8	2795.4	2354.2	1938.6	1522.8	1106.8

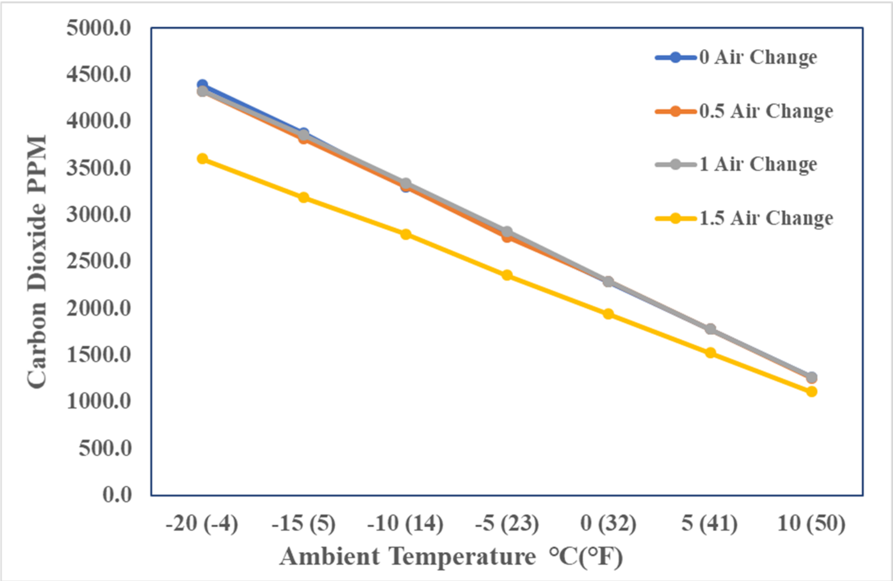


Figure 14. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature.

4.4.2. Constant supply air temperature for direct fired heater

Based on the constant supply air temperature of direct fired heater scenario, carbon dioxide concentration in the space can be calculated. Table 6a-c and Figure 15-17 show the carbon dioxide concentration level in PPM under different air change requirement and 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 6a. Indoor carbon dioxide PPM under different air change requirement and ambient temperature (120°F supply air temperature).

Direct Fired Heating@120°F	**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

Table 6b. Indoor carbon dioxide PPM under different air change requirement and ambient temperature (140°F supply air temperature).

Direct Fired Heating@140°F	**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 6c. Indoor carbon dioxide PPM under different air change requirement and ambient temperature (160℉ supply air temperature).

Direct Fired Heating@160°F	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

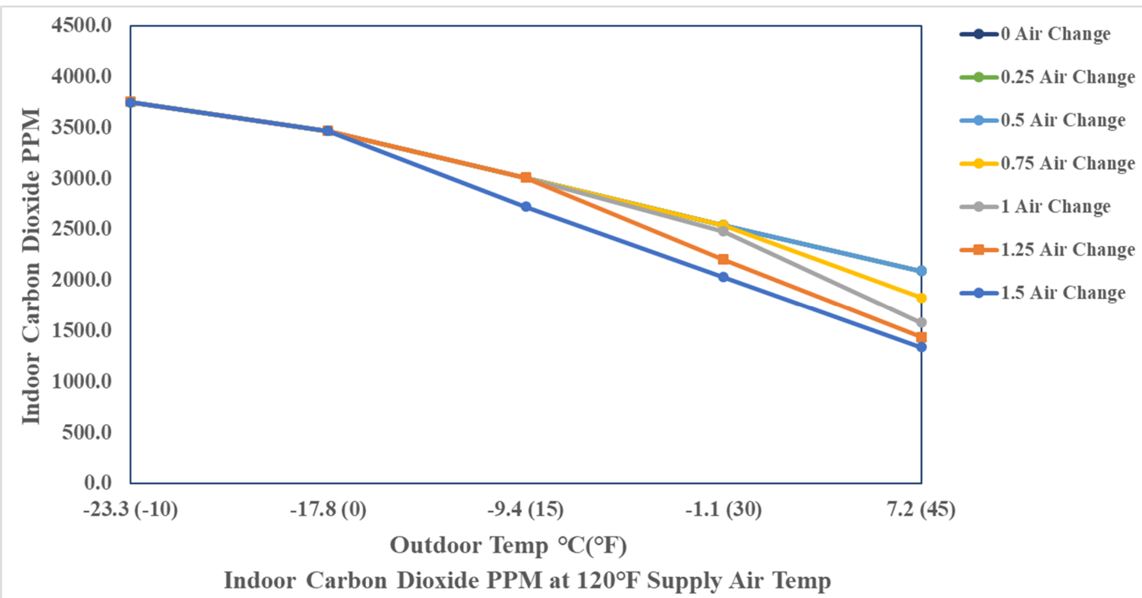


Figure 15. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature @ 120℉ supply air temperature.

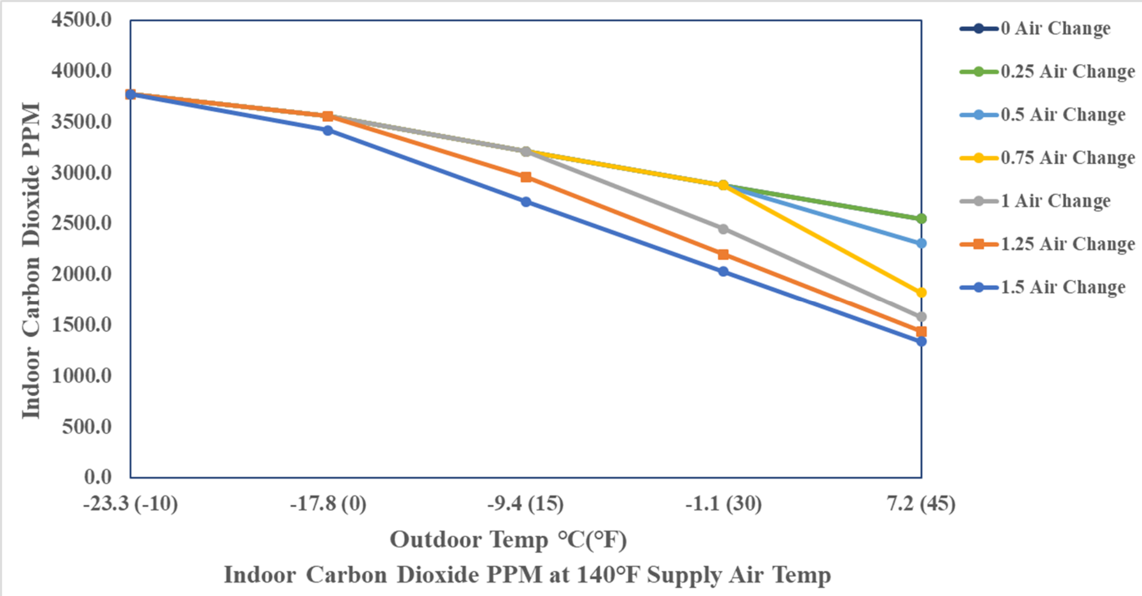


Figure 16. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature @ 140℉ supply air temperature.

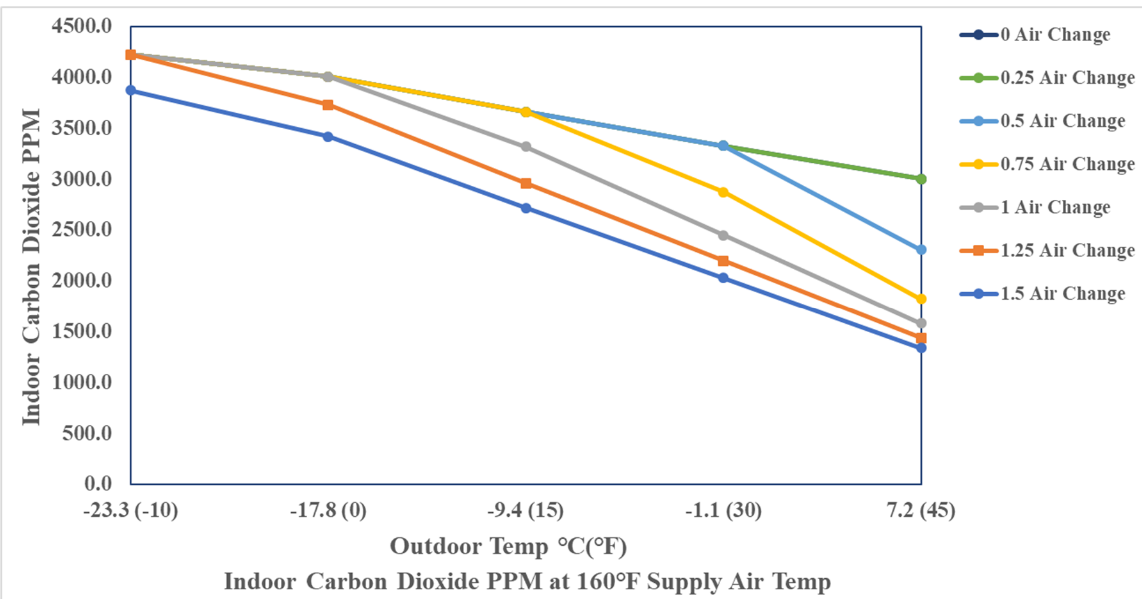


Figure 17. Indoor carbon dioxide PPM level under different air change requirement and ambient temperature @ 160℉ supply air temperature.

4.4.3. Carbon dioxide concentration requirement

According to ASHRAE standard 62.1-2013, carbon dioxide concentration is indicated as poor over 1,500 PPM [17]. For the direct fired heating system, even we don't 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 won't 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.

4.5. 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 7.

Table 7. 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

4.5.1. 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.

4.5.1.1. Heat loss coefficient

Table 8 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. It's only related to air change requirement. At low air change requirement, systematic energy efficiency is more sensitive to the heat loss coefficient. As air change requirement increases, the sensitivity will decrease. 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.

Table 8. 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	0.452	0.452	0.452	0.452	0.452	0.452	0.452	0.452	0.452
0.25	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299	0.299
0.5	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181	0.181
0.75	0.089	0.089	0.089	0.089	0.089	0.089	0.089	0.089	0.089
1	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
1.25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

4.5.1.2. 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.

4.5.1.3. Air change requirement

Table 9 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. It’s 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. 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.

Table 9. 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

4.5.1.4. Sensitivity comparison

Figure 18 shows the sensitivity comparison between air change requirement and heat loss coefficient. 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.

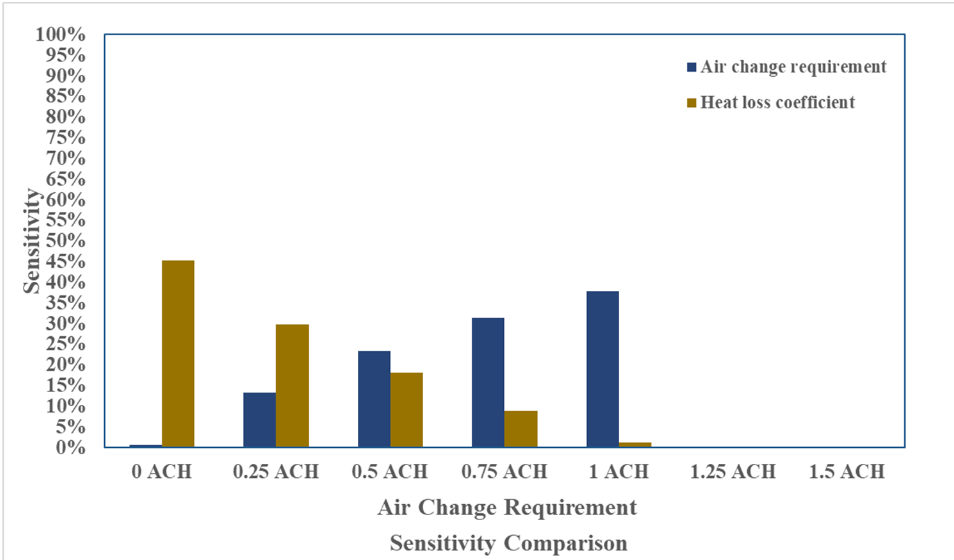


Figure 18. Sensitivity comparison (constant air flow rate).

4.5.2. Constant supply air temperature

Under constant supply air temperature of direct fired heater condition. Calculation results in section 4.2 are used as the benchmark in this sensitivity analysis.

4.5.2.1. Heat loss coefficient

Table 10a-c and Figure 19-21 show the sensitivity of heat loss coefficient under different air change requirement and ambient temperature, at 120°F, 140°F and 160°F supply air temperature respectively. Minus 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 won't 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.

Table 10a. Sensitivity of heat loss coefficient @ 120℉ supply air temperature

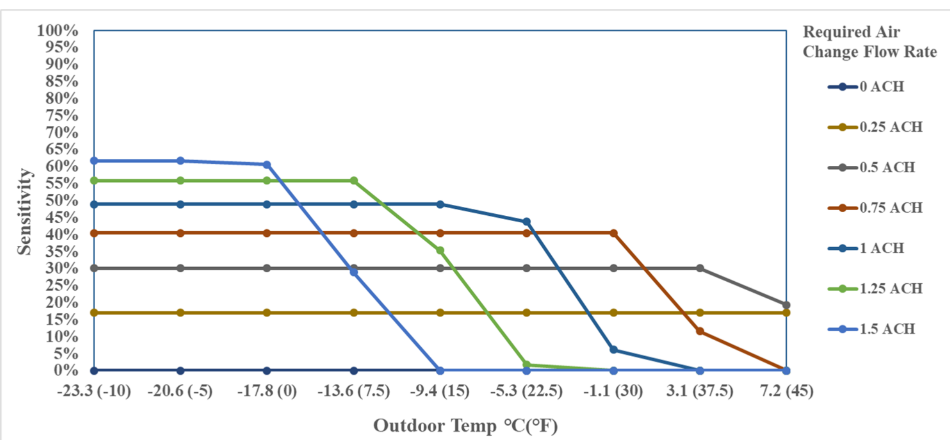
120°F supply air temp	**Ambient T °C (°F)**								
	-23.3 (-10)	**-20.6 (-5)**	**-17.8 (0)**	**-13.6 (7.5)**	**-9.4 (15)**	**-5.3 (22.5)**	**-1.1 (30)**	**3.1 (37.5)**	**7.2 (45)**
0 ACH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.25 ACH	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-0.171	-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 10b. Sensitivity of heat loss coefficient @ 140℉ 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	0.000	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 10c. Sensitivity of heat loss coefficient @ 160℉ 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	0.000	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



Sensitivity of Heat Loss Coefficient @ 120°F Supply Air Temperature

Figure 19. Sensitivity of heat loss coefficient @ 120℉ supply air temperature.

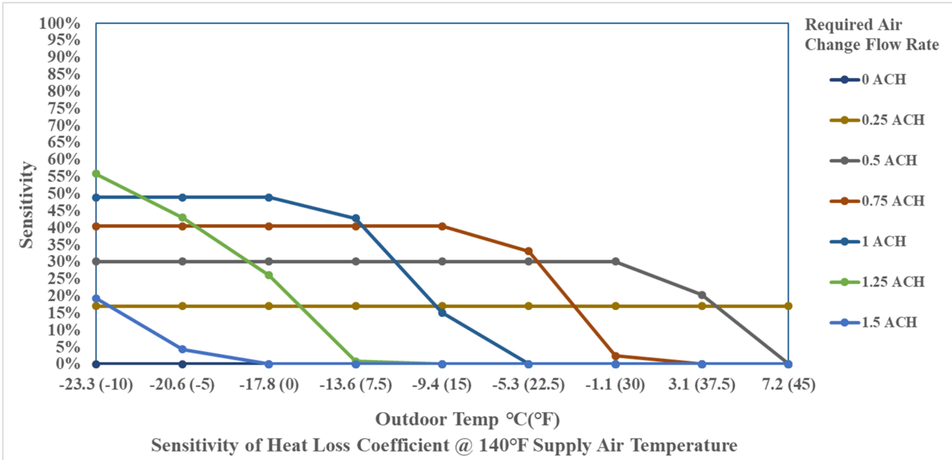


Figure 20. Sensitivity of heat loss coefficient @ 140℉ supply air temperature.

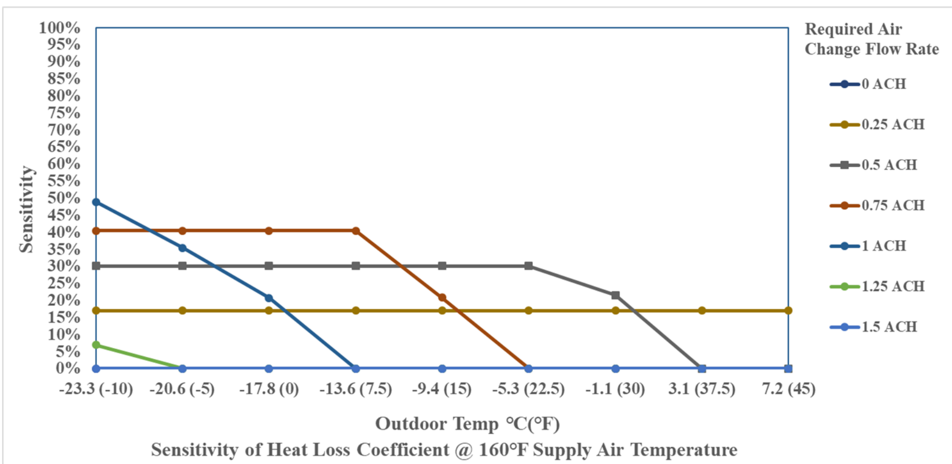


Figure 21. Sensitivity of heat loss coefficient @ 160℉ supply air temperature.

4.5.2.2. Ambient temperature

Table 11a-c and Figure 22-23 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. At a certain ambient temperature baseline, sensitivity maintains as air change rate increases. But after the air change rate goes higher than supply air flow rate, the sensitivity will drop to 0.

Table 11a. Sensitivity of ambient temp @ 120℉ supply air temperature

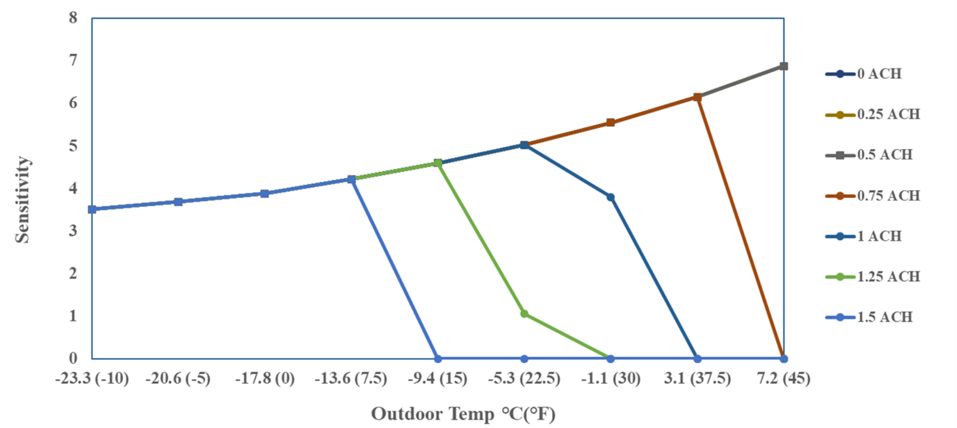
120°F supply air temp	Ambient T °C (°F)								
	-23.3 (-10)	-20.6 (-5)	-17.8 (0)	-13.6 (7.5)	-9.4 (15)	-5.3 (22.5)	-1.1 (30)	3.1 (37.5)	7.2 (45)
0 ACH	3.504	3.681	3.881	4.213	4.595	5.025	5.541	6.153	6.871
0.25 ACH	3.504	3.681	3.881	4.213	4.595	5.025	5.541	6.153	6.871
0.5 ACH	3.504	3.681	3.881	4.213	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 11b. Sensitivity of ambient temp @ 140℉ 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	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 11c. Sensitivity of ambient temp @ 160℉ 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	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



Sensitivity of Ambient Temp @ 120°F Supply Air Temperature

Figure 22. Sensitivity of ambient temp @ 120℉ supply air temperature.

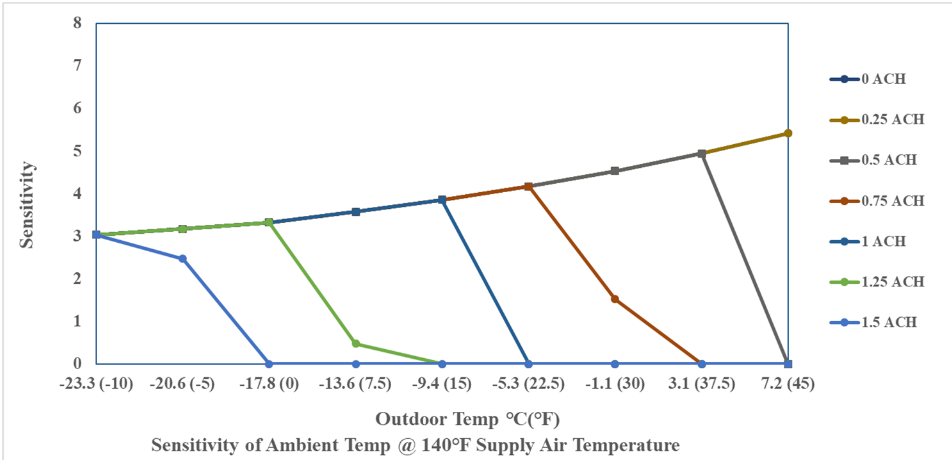


Figure 23. Sensitivity of ambient temp @ 140℉ supply air temperature.

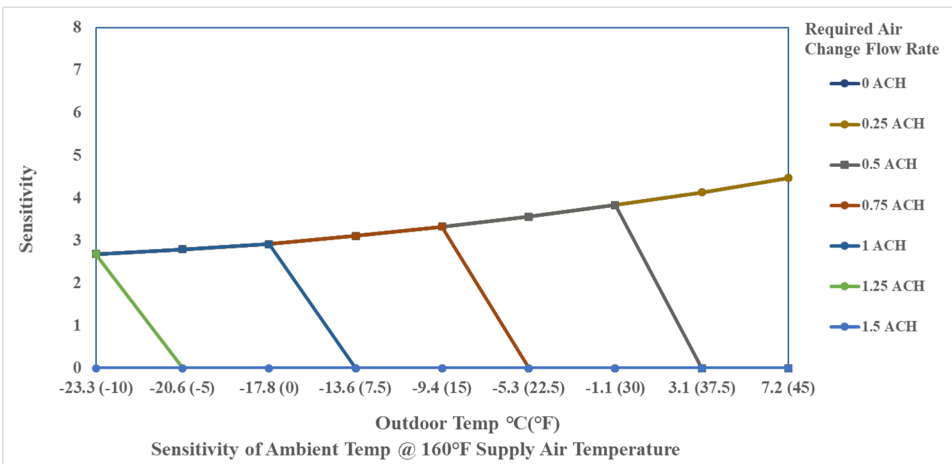


Figure 24. Sensitivity of ambient temp @ 160℉ supply air temperature.

4.5.2.3. Air change requirement

Table 12a-c and Figure 25-27 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 won’t 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.

Table 12a. Sensitivity of air change requirement @ 120°F supply air temperature

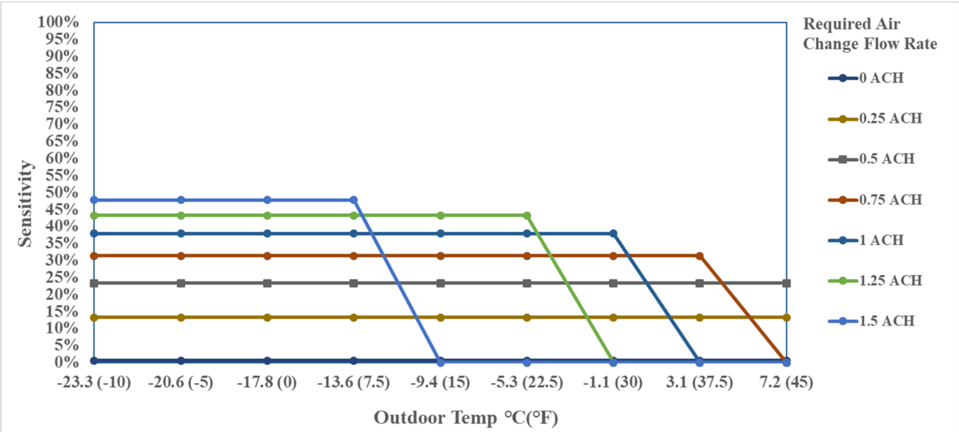
120°F supply air temp	**Ambient T °C (°F)**								
	-23.3 (-10)	**-20.6 (-5)**	**-17.8 (0)**	**-13.6 (7.5)**	**-9.4 (15)**	**-5.3 (22.5)**	**-1.1 (30)**	**3.1 (37.5)**	**7.2 (45)**
0 ACH	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
0.25 ACH	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132	0.132
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 12b. Sensitivity of air change requirement @ 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 13c. Sensitivity of air change requirement @ 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



Sensitivity of Air Change Requirement @ 120°F Supply Air Temperature

Figure 25. Sensitivity of air change requirement @ 120℉ supply air temperature.

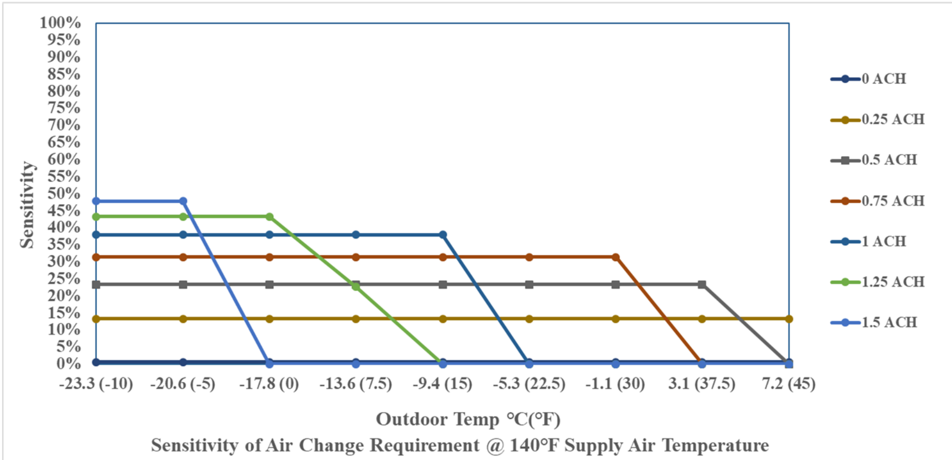


Figure 26. Sensitivity of air change requirement @ 140℉ supply air temperature.

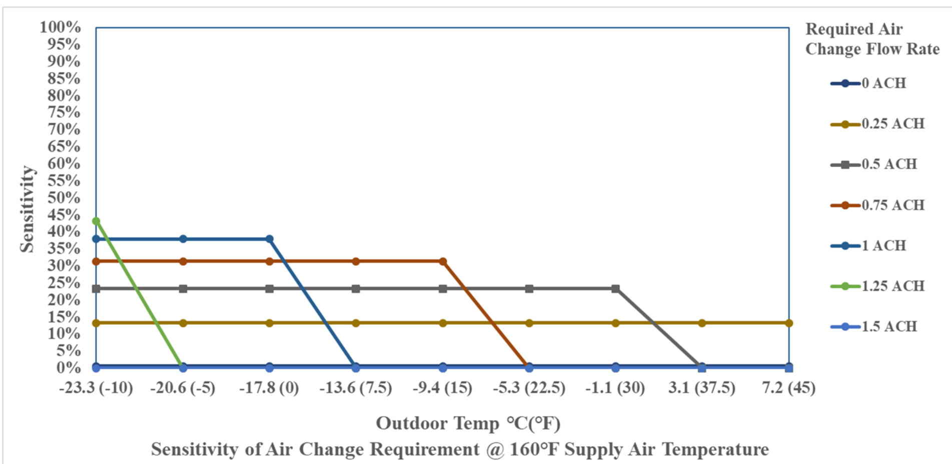


Figure 27. Sensitivity of air change requirement @ 160℉ supply air temperature.

4.5.2.4. 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.

4.6. Evaluation of systematic energy efficiency of direct fired heating system

In order to evaluate the systematic energy efficiency of a certain direct fired heating system under a certain outdoor air temperature under constant supply air temperature condition, we can use calculations based on theoretical thermodynamic foundations. The methodology is shown in section 4.6.1. To quick check the systematic energy efficiency of direct fired heating system, a table is also created in section 4.6.2. With input data (heat loss coefficient, ambient air temperature, air change rate and supply air temperature of heater), we can look up the systematic energy efficiency at a certain condition.

4.6.1. Theoretical calculation

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 [18]:

$$\dot{Q}_{envelope} = (U_{walls} \times A_{walls} + U_{roof} \times A_{roof}) \times (T_{in} - T_{out}) \tag{16}$$

Where,
$\dot{Q}_{envelope}$ is the heat loss through envelope, W (Btu/h)
U_{walls} is the overall thermal transmittance of walls, W/(m^2 K) (Btu/(ft^2 h °F))
U_{roof} is the overall thermal transmittance of roof, W/(m^2 K) (Btu/(ft^2 h °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, ℃ (°F)
T_{out} is the outdoor (ambient) temperature, ℃ (°F)

The heat loss through essential air change can be calculated as [19,20]:

$$\dot{Q}_{air\ change} = c_p \times \dot{m}_{air\ change} \times (T_{in} - T_{out}) \tag{17}$$

$$\dot{m}_{air\ change} = ACH \times \frac{V \times \rho}{3600} \tag{18}$$

Where,
$\dot{Q}_{air\ change}$ is the heat loss through essential air change, W (Btu/h)
c_p is the isobaric specific heat of air, J/(kg K) (Btu/(lbm °F))
$\dot{m}_{air\ change}$ is the mass flow rate of required air change, kg/s (lbm/s)
ACH is the 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)

So,

$$Heating\ Load = \dot{Q}_{envelope} + \dot{Q}_{air\ change} \tag{19}$$

Now we need to calculate the actual natural gas consumption. The energy input rate can be calculated as [19]:

$$\dot{Q}_{input} = c_p \times \dot{m} \times (T_{supply} - T_{out}) \tag{20}$$

Where,
$\dot{m}$ 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 heat load if $\dot{m}$ is excat the same as $\dot{m}_{air\ change}$. Then we can get a result of $\dot{m}$.

In different scenario, $\dot{m}_{air\ change}$ could be different. When the given $\dot{m}_{air\ change}$ is lower than the value we calculated in the previous procedure, it means the heater provides more fresh air than what is required. So use the following equation to calculate the systematic energy efficiency [1]:

$$\eta_{SYS} = \frac{Heating\ Load}{\dot{Q}_{input}/\eta_{heater}} = \frac{\dot{Q}_{envelope} + c_p \times \dot{m}_{air\ change} \times (T_{in} - T_{out})}{c_p \times \dot{m} \times (T_{supply} - T_{out})/\eta_{heater}} \tag{21}$$

Where,
η_{heater} is the heater device efficiency

When the given $\dot{m}_{air\ change}$ 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 the following equation to recalculate the $\dot{m}$:

$$c_p \times \dot{m} \times \left(T_{supply} - T_{out}\right) = \dot{Q}_{envelope} + c_p \times \dot{m}_{air\ change} \times (T_{in} - T_{out}) \tag{22}$$

Then the systematic energy efficiency will be:

$$\eta_{SYS} = \frac{Heating\ Load}{\dot{Q}_{input}/\eta_{heater}} = \frac{\dot{Q}_{envelope} + c_p \times \dot{m}_{air\ change} \times (T_{in} - T_{out})}{c_p \times \dot{m} \times (T_{supply} - T_{out})/\eta_{heater}} = \eta_{heater} \tag{23}$$

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.

4.6.2. By chart and table

We can also use charts and table to look up the systematic energy efficiency under certain condition.

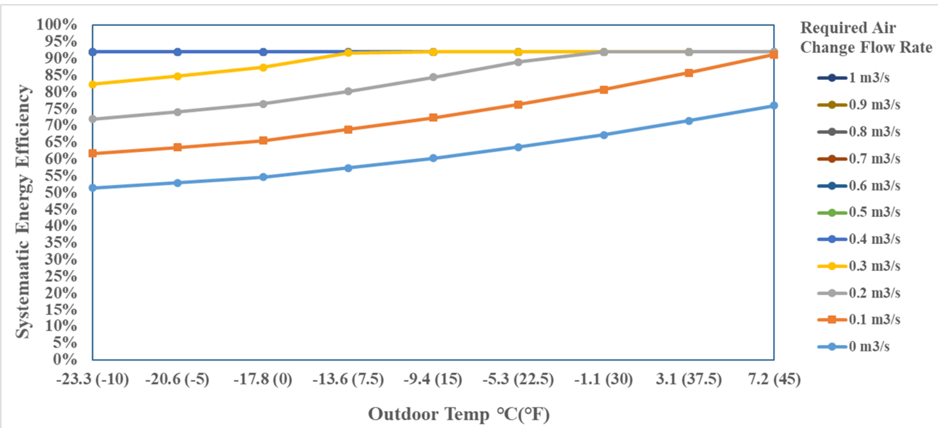
First, we need to calculate the heat loss coefficient through building envelope and the volume flow rate of required air change by the following equations:

$$Heat\ Loss\ Coefficient = (U_{walls} \times A_{walls} + U_{roof} \times A_{roof}) \tag{24}$$

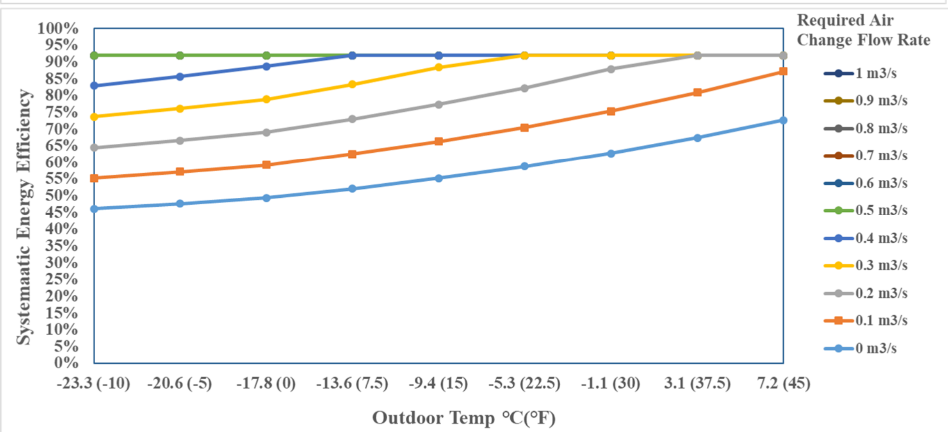
$$Volume\ Flow\ Rate\ of\ Required\ Air\ Change = \frac{V \times ACH}{3600} \tag{25}$$

With the calculated heat loss coefficient through building envelope and the volume flow rate of required air change, as well as the selected supply air temperature, we can use Table A1 in the appendix to look up the systematic energy efficiency for the direct fired heating system. Table A1 can be used for 65°F (18.3°C) space temperature setting.

Below charts show results for an example of 500 W/K (948 Btu/(h °F)) heat loss coefficient, 160°F/140°F/120°F supply air temperature.



Systematic Energy Efficiency @ 160°F Supply Air Temperature



Systematic Energy Efficiency @ 140°F Supply Air Temperature

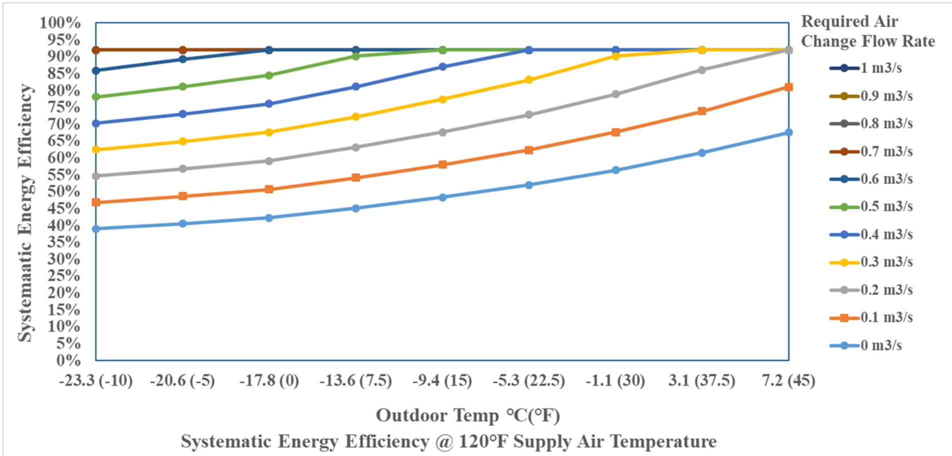


Figure 28. Systematic energy efficiency for direct fired heating system @ 500 W/K (948 Btu/(h °F)) heat loss coefficient.

5. Conclusion

In this research, systematic energy efficiency of direct and indirect fired heating system are analyzed based on different conditions. Indirect fired heating system always has a constant systematic energy efficiency which is same as the heater's device efficiency. For direct fired heating system, input parameters such as control method (constant air flow rate or constant supply air temperature), ambient temperature, air change rate and heat loss coefficent of the building envelope will impact the systematic energy efficiency. Sensitivity study of each parameter shows that different parameters have different sensitivity towards the systematic energy efficiency. Systematic and single heater exergy efficiencies are also studied in this research to help understand the irreversibility of the heating systems. Carbon dioxide concentration level is studied for direct fired heating system to evaluate the indoor air quality when using direct fired heater under specific conditions.

5.1. Systematic energy efficiency (Constant air flow rate for direct fired heater)

1) For indirect fired heating system, the systematic energy efficiency remains constant at different outdoor air temperature and air change requirement. The Systematic efficiency is equal to the heater 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 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 a inflection point,

the natural gas demand of direct fired heating system will become lower than indirect fired heating system.

5.2. Systematic energy efficiency (Constant supply air temperature for direct fired heater)

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.
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

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. It’s 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 PPM

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.

5.5. Sensitivity analysis

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.

Based on the results and conclusion of this research, it is known that direct fired heaters don't 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. When choosing heating equipments for differnt buildings under different conditions, systematic energy efficiency needs to be considered in order to achieve energy conservation. 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 comfirt level because the combustion of direct fired heaters will generate more carbon dioxide in the space.

Nomenclature

c	specific heat, J/(kg 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
$\dot{Q}$	heat transfer rate, kW
$\dot{q}$	volumetric flow rate, m^3/s
$\bar{R}$	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

Greek symbols

η	energy efficiency
ε	exergy efficiency
ρ	density, kg/m^3

Subscripts and superscripts

atm	atmosphere

com	combustion
CV	control volume
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

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

References

[1] Bejan A. Advanced engineering thermodynamics. John Wiley & Sons; 2016 Sep 19.

[2] ASHRAE A. Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA. 2013.

[3] Rivero RA, Garfias M. Standard chemical exergy of elements updated. Energy. 2006 Dec 1;31(15):3310-26.

[4] Ertesvåg IS. Sensitivity of chemical exergy for atmospheric gases and gaseous fuels to variations in ambient conditions. Energy Conversion and Management. 2007 Jul 1;48(7):1983-95.

[5] .Szargut J. Exergy Method, Technical and Ecological Applications. Southampton, UK: WIT Press; 2005.

[6] Engineering ToolBox, (2004). Carbon Dioxide Concentrations in Rooms with People – Available at: <https://www.engineeringtoolbox.com/pollution-concentration-rooms-d_692.html> [accessed 20.05.2019].

[7] North American Energy Standards Board. Natural Gas Specs Sheet – Available at:<https://www.naesb.org/pdf2/wgq_bps100605w2.pdf> [accessed 10.1.2019].

[8] Engineering ToolBox, (2005). Fuel Gases Heating Values – Available at: <https://www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html> [accessed 20.05.2019].

[9] Saltelli A, Ratto M, Andres T, Campolongo F, Cariboni J, Gatelli D, Saisana M, Tarantola S. Global sensitivity analysis: the primer. John Wiley & Sons; 2008 Feb 28.

[10] Younes C, Shdid CA, Bitsuamlak G. Air infiltration through building envelopes: A review. Journal of Building physics. 2012 Jan;35(3):267-302.

[11] CO2 Earth. Carbon dioxide level of the atmosphere – Available at: < https://www.co2.earth/> [accessed 25.05.2019].

[12] United States Environmental Protection Agency, EPA. Building codes and indoor air quality – Available at:< https://www.epa.gov/sites/production/files/2014-08/documents/building_codes_and_iaq.pdf> [accessed 20.12.2018].

[13] The official web site of TITAN. Direct Fired vs. Indirect Fired Heaters – Available at:< http://www.titan-air.com/direct-fired-vs.-indirect-fired-heaters.html> [accessed 20.9.2018].

[14] Cambridge Engineering INC. S-Series Direct Gas-Fired Blow-Thru® Space Heaters – Available at:< https://www.cambridge-eng.com/Portals/0/pdf/specs/S-ES.pdf> [accessed 05.11.2018].

[15] Engineering ToolBox, (2003). Fuels Exhaust Temperatures – Available at: <https://www.engineeringtoolbox.com/fuels-exhaust-temperatures-d_168.html> [accessed 15.1.2019].

[16] Air Conditioning Contractors of America. Manual N (Commercial Load Calculation) – Available at: <https://www.acca.org/standards/technical-manuals> [accessed 17.12.2018].

[17] ASHRAE A. Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA. 2013.

[18] Bergman TL, Incropera FP, Lavine AS, DeWitt DP. Introduction to heat transfer. John Wiley & Sons; 2011 Jun 13.

[19] Cengel YA, Boles MA. Thermodynamics: an engineering approach. United States: McGraw-Hill; 2002.

[20] Halliday D, Walker J, Resnick R. Fundamentals of physics. John Wiley & Sons; 2013 Aug 13.

Appendix

Table A1. Direct Fired heating systematic energy efficiency under different conditions (65°F space temperature setting)

Heat Loss Coefficient Through Envelope		Direct Fired Heater Supply Air Temperature		Air Change Requirement		Ambient T °C (°F)								
W/K	**Btu/(h °F)**	**°C**	**°F**	**m3/s**	**CFM**	**-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)**
500	**948**	**71**	**160**	**0**	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.1	**212**	61.7%	63.5%	65.5%	68.8%	72.4%	76.3%	80.7%	85.7%	91.2%
				0.2	**424**	72.0%	74.1%	76.4%	80.2%	84.4%	89.0%	92.0%	92.0%	92.0%
				0.3	**636**	82.3%	84.7%	87.4%	91.7%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.4	**848**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.5	**1,060**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.6	**1,271**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.7	**1,483**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.8	**1,695**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.9	**1,907**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1	**2,119**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		60	**140**	**0**	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.1	**212**	55.3%	57.1%	59.2%	62.6%	66.3%	70.5%	75.3%	80.9%	87.2%
				0.2	**424**	64.5%	66.6%	69.0%	73.0%	77.4%	82.3%	87.9%	92.0%	92.0%
				0.3	**636**	73.7%	76.2%	78.9%	83.4%	88.4%	92.0%	92.0%	92.0%	92.0%
				0.4	**848**	82.9%	85.7%	88.8%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.5	**1,060**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.6	**1,271**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.7	**1,483**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.8	**1,695**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.9	**1,907**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1	**2,119**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		49	**120**	**0**	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.1	**212**	46.9%	48.7%	50.7%	54.1%	58.0%	62.4%	67.7%	73.8%	81.1%
				0.2	**424**	54.7%	56.8%	59.2%	63.2%	67.7%	72.8%	78.9%	86.1%	92.0%
				0.3	**636**	62.5%	64.9%	67.7%	72.2%	77.4%	83.2%	90.2%	92.0%	92.0%
				0.4	**848**	70.3%	73.0%	76.1%	81.2%	87.1%	92.0%	92.0%	92.0%	92.0%
				0.5	**1,060**	78.1%	81.2%	84.6%	90.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.6	**1,271**	85.9%	89.3%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.7	**1,483**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.8	**1,695**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.9	**1,907**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1	**2,119**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
1,000	**1,896**	**71**	**160**	**0**	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%

				0.2	**424**	61.7%	63.5%	65.5%	68.8%	72.4%	76.3%	80.7%	85.7%	91.2%
				0.4	**848**	72.0%	74.1%	76.4%	80.2%	84.4%	89.0%	92.0%	92.0%	92.0%
				0.6	**1,271**	82.3%	84.7%	87.4%	91.7%	92.0%	92.0%	92.0%	92.0%	92.0%
				0.8	**1,695**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1	**2,119**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.2	**2,543**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.4	**2,967**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.6	**3,390**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.8	**3,814**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2	**4,238**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		60	**140**	**0**	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.2	**424**	55.3%	57.1%	59.2%	62.6%	66.3%	70.5%	75.3%	80.9%	87.2%
				0.4	**848**	64.5%	66.6%	69.0%	73.0%	77.4%	82.3%	87.9%	92.0%	92.0%
				0.6	**1,271**	73.7%	76.2%	78.9%	83.4%	88.4%	92.0%	92.0%	92.0%	92.0%
				0.8	**1,695**	82.9%	85.7%	88.8%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1	**2,119**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.2	**2,543**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.4	**2,967**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.6	**3,390**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.8	**3,814**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2	**4,238**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		49	**120**	**0**	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.2	**424**	46.9%	48.7%	50.7%	54.1%	58.0%	62.4%	67.7%	73.8%	81.1%
				0.4	**848**	54.7%	56.8%	59.2%	63.2%	67.7%	72.8%	78.9%	86.1%	92.0%
				0.6	**1,271**	62.5%	64.9%	67.7%	72.2%	77.4%	83.2%	90.2%	92.0%	92.0%
				0.8	**1,695**	70.3%	73.0%	76.1%	81.2%	87.1%	92.0%	92.0%	92.0%	92.0%
				1	**2,119**	78.1%	81.2%	84.6%	90.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.2	**2,543**	85.9%	89.3%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.4	**2,967**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.6	**3,390**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.8	**3,814**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2	**4,238**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
1,500	**2,843**	**71**	**160**	**0**	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.25	**530**	60.0%	61.8%	63.7%	66.9%	70.4%	74.1%	78.5%	83.3%	88.7%
				0.5	**1,060**	68.6%	70.6%	72.8%	76.4%	80.4%	84.7%	89.7%	92.0%	92.0%
				0.75	**1,589**	77.1%	79.4%	81.9%	86.0%	90.5%	92.0%	92.0%	92.0%	92.0%
				1	**2,119**	85.7%	88.2%	91.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.25	**2,649**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.5	**3,179**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.75	**3,708**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2	**4,238**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.25	**4,768**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.5	**5,298**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%

				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.25	**530**	53.7%	55.5%	57.5%	60.8%	64.5%	68.5%	73.3%	78.7%	84.8%
				0.5	**1,060**	61.4%	63.5%	65.7%	69.5%	73.7%	78.3%	83.7%	89.9%	92.0%
				0.75	**1,589**	69.1%	71.4%	74.0%	78.2%	82.9%	88.1%	92.0%	92.0%	92.0%
				1	**2,119**	76.8%	79.3%	82.2%	86.9%	92.0%	92.0%	92.0%	92.0%	92.0%
		60	**140**	**1.25**	**2,649**	84.4%	87.3%	90.4%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.5	**3,179**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.75	**3,708**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2	**4,238**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.25	**4,768**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.5	**5,298**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.25	**530**	45.6%	47.3%	49.3%	52.6%	56.4%	60.7%	65.8%	71.8%	78.8%
				0.5	**1,060**	52.1%	54.1%	56.4%	60.2%	64.5%	69.4%	75.2%	82.0%	90.1%
				0.75	**1,589**	58.6%	60.9%	63.4%	67.7%	72.5%	78.0%	84.6%	92.0%	92.0%
				1	**2,119**	65.1%	67.6%	70.5%	75.2%	80.6%	86.7%	92.0%	92.0%	92.0%
		49	**120**	**1.25**	**2,649**	71.6%	74.4%	77.5%	82.7%	88.7%	92.0%	92.0%	92.0%	92.0%
				1.5	**3,179**	78.1%	81.2%	84.6%	90.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.75	**3,708**	84.6%	87.9%	91.6%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2	**4,238**	91.2%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.25	**4,768**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.5	**5,298**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.3	**636**	59.1%	60.9%	62.8%	65.9%	69.3%	73.1%	77.3%	82.1%	87.4%
				0.6	**1,271**	66.8%	68.8%	71.0%	74.5%	78.4%	82.6%	87.4%	92.0%	92.0%
				0.9	**1,907**	74.6%	76.7%	79.2%	83.1%	87.4%	92.0%	92.0%	92.0%	92.0%
				1.2	**2,543**	82.3%	84.7%	87.4%	91.7%	92.0%	92.0%	92.0%	92.0%	92.0%
		71	**160**	**1.5**	**3,179**	90.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.8	**3,814**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.1	**4,450**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.4	**5,086**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.7	**5,721**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
2,000	**3,791**			**3**	**6,357**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.3	**636**	53.0%	54.7%	56.7%	59.9%	63.6%	67.6%	72.2%	77.5%	83.6%
				0.6	**1,271**	59.9%	61.9%	64.1%	67.8%	71.9%	76.4%	81.6%	87.7%	92.0%
				0.9	**1,907**	66.8%	69.0%	71.5%	75.6%	80.2%	85.2%	91.0%	92.0%	92.0%
		60	**140**	**1.2**	**2,543**	73.7%	76.2%	78.9%	83.4%	88.4%	92.0%	92.0%	92.0%	92.0%
				1.5	**3,179**	80.6%	83.3%	86.3%	91.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				1.8	**3,814**	87.5%	90.4%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.1	**4,450**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.4	**5,086**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.7	**5,721**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%

				3	**6,357**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.3	**636**	44.9%	46.7%	48.6%	51.9%	55.6%	59.8%	64.8%	70.8%	77.7%
				0.6	**1,271**	50.8%	52.8%	55.0%	58.7%	62.9%	67.6%	73.3%	80.0%	87.8%
				0.9	**1,907**	56.6%	58.8%	61.3%	65.4%	70.1%	75.4%	81.7%	89.2%	92.0%
				1.2	**2,543**	62.5%	64.9%	67.7%	72.2%	77.4%	83.2%	90.2%	92.0%	92.0%
		49	**120**	**1.5**	**3,179**	68.4%	71.0%	74.0%	79.0%	84.6%	91.0%	92.0%	92.0%	92.0%
				1.8	**3,814**	74.2%	77.1%	80.3%	85.7%	91.9%	92.0%	92.0%	92.0%	92.0%
				2.1	**4,450**	80.1%	83.2%	86.7%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.4	**5,086**	85.9%	89.3%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.7	**5,721**	91.8%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.4	**848**	59.6%	61.4%	63.3%	66.5%	70.0%	73.7%	78.0%	82.8%	88.2%
				0.8	**1,695**	67.9%	69.9%	72.1%	75.6%	79.6%	83.9%	88.8%	92.0%	92.0%
				1.2	**2,543**	76.1%	78.3%	80.8%	84.8%	89.2%	92.0%	92.0%	92.0%	92.0%
				1.6	**3,390**	84.3%	86.8%	89.5%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		71	**160**	**2**	**4,238**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.4	**5,086**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.8	**5,933**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.2	**6,781**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.6	**7,628**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4	**8,476**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.4	**848**	53.4%	55.2%	57.2%	60.5%	64.1%	68.2%	72.8%	78.2%	84.3%
				0.8	**1,695**	60.8%	62.8%	65.1%	68.8%	73.0%	77.6%	82.9%	89.0%	92.0%
				1.2	**2,543**	68.2%	70.4%	73.0%	77.1%	81.8%	87.0%	92.0%	92.0%	92.0%
2,500	**4,739**			**1.6**	**3,390**	75.5%	78.1%	80.9%	85.5%	90.7%	92.0%	92.0%	92.0%	92.0%
		60	**140**	**2**	**4,238**	82.9%	85.7%	88.8%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.4	**5,086**	90.3%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.8	**5,933**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.2	**6,781**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.6	**7,628**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4	**8,476**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.4	**848**	45.3%	47.1%	49.0%	52.3%	56.1%	60.3%	65.4%	71.4%	78.4%
				0.8	**1,695**	51.6%	53.6%	55.8%	59.6%	63.8%	68.7%	74.4%	81.2%	89.2%
				1.2	**2,543**	57.8%	60.1%	62.6%	66.8%	71.6%	77.0%	83.4%	91.1%	92.0%
		49	**120**	**1.6**	**3,390**	64.1%	66.6%	69.3%	74.0%	79.3%	85.3%	92.0%	92.0%	92.0%
				2	**4,238**	70.3%	73.0%	76.1%	81.2%	87.1%	92.0%	92.0%	92.0%	92.0%
				2.4	**5,086**	76.6%	79.5%	82.9%	88.4%	92.0%	92.0%	92.0%	92.0%	92.0%
				2.8	**5,933**	82.8%	86.0%	89.6%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.2	**6,781**	89.1%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%

				3.6	**7,628**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4	**8,476**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.5	**1,060**	60.0%	61.8%	63.7%	66.9%	70.4%	74.1%	78.5%	83.3%	88.7%
				1	**2,119**	68.6%	70.6%	72.8%	76.4%	80.4%	84.7%	89.7%	92.0%	92.0%
				1.5	**3,179**	77.1%	79.4%	81.9%	86.0%	90.5%	92.0%	92.0%	92.0%	92.0%
				2	**4,238**	85.7%	88.2%	91.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		71	**160**	**2.5**	**5,298**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.5	**7,417**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4	**8,476**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5	**10,595**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.5	**1,060**	53.7%	55.5%	57.5%	60.8%	64.5%	68.5%	73.3%	78.7%	84.8%
				1	**2,119**	61.4%	63.5%	65.7%	69.5%	73.7%	78.3%	83.7%	89.9%	92.0%
				1.5	**3,179**	69.1%	71.4%	74.0%	78.2%	82.9%	88.1%	92.0%	92.0%	92.0%
				2	**4,238**	76.8%	79.3%	82.2%	86.9%	92.0%	92.0%	92.0%	92.0%	92.0%
3,000	**5,687**	**60**	**140**	**2.5**	**5,298**	84.4%	87.3%	90.4%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.5	**7,417**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4	**8,476**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5	**10,595**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.5	**1,060**	45.6%	47.3%	49.3%	52.6%	56.4%	60.7%	65.8%	71.8%	78.8%
				1	**2,119**	52.1%	54.1%	56.4%	60.2%	64.5%	69.4%	75.2%	82.0%	90.1%
				1.5	**3,179**	58.6%	60.9%	63.4%	67.7%	72.5%	78.0%	84.6%	92.0%	92.0%
				2	**4,238**	65.1%	67.6%	70.5%	75.2%	80.6%	86.7%	92.0%	92.0%	92.0%
		49	**120**	**2.5**	**5,298**	71.6%	74.4%	77.5%	82.7%	88.7%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	78.1%	81.2%	84.6%	90.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.5	**7,417**	84.6%	87.9%	91.6%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4	**8,476**	91.2%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5	**10,595**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.75	**1,589**	62.4%	64.3%	66.3%	69.6%	73.2%	77.2%	81.7%	86.7%	92.0%
				1.5	**3,179**	73.4%	75.6%	78.0%	81.9%	86.1%	90.8%	92.0%	92.0%	92.0%
3,500	**6,634**	**71**	**160**	**2.25**	**4,768**	84.5%	87.0%	89.7%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.75	**7,946**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%

				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.75	**1,589**	55.9%	57.8%	59.9%	63.3%	67.1%	71.3%	76.2%	81.9%	88.2%
				1.5	**3,179**	65.8%	68.0%	70.4%	74.5%	79.0%	83.9%	89.7%	92.0%	92.0%
				2.25	**4,768**	75.7%	78.2%	81.0%	85.6%	90.8%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	85.5%	88.4%	91.6%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		60	**140**	**3.75**	**7,946**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.75	**1,589**	47.4%	49.3%	51.3%	54.8%	58.7%	63.2%	68.5%	74.7%	82.0%
				1.5	**3,179**	55.8%	58.0%	60.4%	64.5%	69.1%	74.3%	80.5%	87.9%	92.0%
				2.25	**4,768**	64.2%	66.7%	69.5%	74.1%	79.5%	85.5%	92.0%	92.0%	92.0%
				3	**6,357**	72.5%	75.4%	78.5%	83.8%	89.8%	92.0%	92.0%	92.0%	92.0%
		49	**120**	**3.75**	**7,946**	80.9%	84.1%	87.6%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	89.3%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.75	**1,589**	61.1%	62.9%	64.8%	68.1%	71.6%	75.5%	79.9%	84.8%	90.2%
				1.5	**3,179**	70.7%	72.8%	75.1%	78.8%	82.9%	87.4%	92.0%	92.0%	92.0%
				2.25	**4,768**	80.3%	82.7%	85.3%	89.5%	92.0%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	90.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		71	**160**	**3.75**	**7,946**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
4,000	**7,582**			**6**	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.75	**1,589**	54.7%	56.5%	58.6%	61.9%	65.6%	69.8%	74.6%	80.1%	86.3%
				1.5	**3,179**	63.3%	65.4%	67.8%	71.7%	76.0%	80.8%	86.3%	92.0%	92.0%
		60	**140**	**2.25**	**4,768**	72.0%	74.4%	77.0%	81.4%	86.4%	91.8%	92.0%	92.0%	92.0%
				3	**6,357**	80.6%	83.3%	86.3%	91.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				3.75	**7,946**	89.2%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%

				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.75	**1,589**	46.4%	48.2%	50.2%	53.6%	57.4%	61.8%	66.9%	73.1%	80.2%
				1.5	**3,179**	53.7%	55.8%	58.1%	62.0%	66.5%	71.5%	77.5%	84.6%	92.0%
				2.25	**4,768**	61.0%	63.4%	66.1%	70.5%	75.6%	81.3%	88.1%	92.0%	92.0%
				3	**6,357**	68.4%	71.0%	74.0%	79.0%	84.6%	91.0%	92.0%	92.0%	92.0%
		49	**120**	**3.75**	**7,946**	75.7%	78.6%	81.9%	87.4%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	83.0%	86.2%	89.8%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	90.3%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.75	**1,589**	60.0%	61.8%	63.7%	66.9%	70.4%	74.1%	78.5%	83.3%	88.7%
				1.5	**3,179**	68.6%	70.6%	72.8%	76.4%	80.4%	84.7%	89.7%	92.0%	92.0%
				2.25	**4,768**	77.1%	79.4%	81.9%	86.0%	90.5%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	85.7%	88.2%	91.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
		71	**160**	**3.75**	**7,946**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.75	**1,589**	53.7%	55.5%	57.5%	60.8%	64.5%	68.5%	73.3%	78.7%	84.8%
4,500	**8,530**			**1.5**	**3,179**	61.4%	63.5%	65.7%	69.5%	73.7%	78.3%	83.7%	89.9%	92.0%
				2.25	**4,768**	69.1%	71.4%	74.0%	78.2%	82.9%	88.1%	92.0%	92.0%	92.0%
				3	**6,357**	76.8%	79.3%	82.2%	86.9%	92.0%	92.0%	92.0%	92.0%	92.0%
		60	**140**	**3.75**	**7,946**	84.4%	87.3%	90.4%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.75	**1,589**	45.6%	47.3%	49.3%	52.6%	56.4%	60.7%	65.8%	71.8%	78.8%
		49	**120**	**1.5**	**3,179**	52.1%	54.1%	56.4%	60.2%	64.5%	69.4%	75.2%	82.0%	90.1%
				2.25	**4,768**	58.6%	60.9%	63.4%	67.7%	72.5%	78.0%	84.6%	92.0%	92.0%
				3	**6,357**	65.1%	67.6%	70.5%	75.2%	80.6%	86.7%	92.0%	92.0%	92.0%
				3.75	**7,946**	71.6%	74.4%	77.5%	82.7%	88.7%	92.0%	92.0%	92.0%	92.0%

				4.5	**9,536**	78.1%	81.2%	84.6%	90.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	84.6%	87.9%	91.6%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	91.2%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	51.4%	52.9%	54.6%	57.3%	60.3%	63.5%	67.2%	71.4%	76.0%
				0.75	**1,589**	59.1%	60.9%	62.8%	65.9%	69.3%	73.1%	77.3%	82.1%	87.4%
				1.5	**3,179**	66.8%	68.8%	71.0%	74.5%	78.4%	82.6%	87.4%	92.0%	92.0%
				2.25	**4,768**	74.6%	76.7%	79.2%	83.1%	87.4%	92.0%	92.0%	92.0%	92.0%
				3	**6,357**	82.3%	84.7%	87.4%	91.7%	92.0%	92.0%	92.0%	92.0%	92.0%
		71	**160**	**3.75**	**7,946**	90.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	46.1%	47.6%	49.3%	52.1%	55.3%	58.8%	62.8%	67.4%	72.7%
				0.75	**1,589**	53.0%	54.7%	56.7%	59.9%	63.6%	67.6%	72.2%	77.5%	83.6%
				1.5	**3,179**	59.9%	61.9%	64.1%	67.8%	71.9%	76.4%	81.6%	87.7%	92.0%
				2.25	**4,768**	66.8%	69.0%	71.5%	75.6%	80.2%	85.2%	91.0%	92.0%	92.0%
				3	**6,357**	73.7%	76.2%	78.9%	83.4%	88.4%	92.0%	92.0%	92.0%	92.0%
5,000	**9,478**	**60**	**140**	**3.75**	**7,946**	80.6%	83.3%	86.3%	91.2%	92.0%	92.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	87.5%	90.4%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				0	**0**	39.1%	40.6%	42.3%	45.1%	48.4%	52.0%	56.4%	61.5%	67.6%
				0.75	**1,589**	44.9%	46.7%	48.6%	51.9%	55.6%	59.8%	64.8%	70.8%	77.7%
				1.5	**3,179**	50.8%	52.8%	55.0%	58.7%	62.9%	67.6%	73.3%	80.0%	87.8%
				2.25	**4,768**	56.6%	58.8%	61.3%	65.4%	70.1%	75.4%	81.7%	89.2%	92.0%
				3	**6,357**	62.5%	64.9%	67.7%	72.2%	77.4%	83.2%	90.2%	92.0%	92.0%
		49	**120**	**3.75**	**7,946**	68.4%	71.0%	74.0%	79.0%	84.6%	91.0%	92.0%	92.0%	92.0%
				4.5	**9,536**	74.2%	77.1%	80.3%	85.7%	91.9%	92.0%	92.0%	92.0%	92.0%
				5.25	**11,125**	80.1%	83.2%	86.7%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6	**12,714**	85.9%	89.3%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				6.75	**14,303**	91.8%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%
				7.5	**15,893**	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%	92.0%