Simulator for Teaching Process Heater Operating Principles

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Abstract

Process heaters are used in the hydrocarbon and chemical processing industries (HPI/CPI) to heat hydrocarbon fluids that are being converted into fuels like gasoline or chemicals like ethylene. Process heater operation involves combustion, heat transfer, and fluid flow principles. It is not practical to use an actual working heater to teach these principles. This paper describes an electronic heater simulator that was developed for instructing engineers and operators on heater and burner operation.

Introduction

Simulators have been used for many years in, for example, the nuclear and aerospace industries to simulate both normal operating conditions as well as potentially dangerous situations. The latter may rarely if ever be seen in actual practice, but it is imperative that operators be prepared for them in the event they ever do occur. In either case, it is generally not practical or preferable to let new operators learn initially on the actual equipment because of the potentially dangerous consequences of making a mistake. Even if an operating error did not result in an unsafe condition, it could result in lost production or reduced efficiency that could have detrimental economic ramifications for a plant. For these reasons, most new operators would be hesitant to make adjustments on this type of equipment until they have had sufficient training. The challenge is to give them adequate training before they work with the real equipment.

Process heaters (see Figure 1) are used in the chemical and refining industries to heat hydrocarbon fluids flowing through tubes inside the radiant and convection sections. These heaters are designed to increase the fluid temperature for further processing in some type of downstream reactor. Most plants have numerous heaters in a variety of configurations operating under a variety of conditions. The basic job of the operator is to make sure the heaters safely elevate the process fluid temperature to the target level, while maximizing thermal efficiency and minimizing pollution emissions. The main adjustments made to the heater are the fuel and combustion air flow rates and the pressure levels inside the heater. The adjustments are made by adjusting the fuel flow control valve(s), the burner dampers, and the stack damper. The latter two are frequently manually controlled.

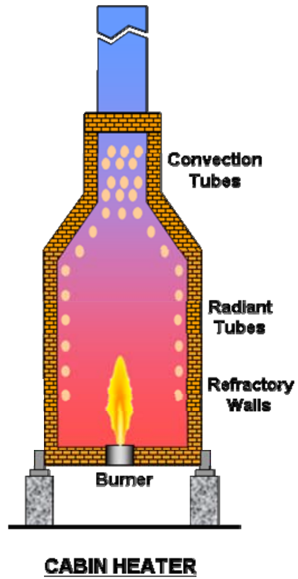


Figure 1. Schematic of a typical process heater.

Process Heater Operating Principles

Combustion

Large amounts of fuel are combusted to convert the chemical energy into useful thermal energy to heat the fluids flowing through the process heaters. Burners are used to safely control the combustion process to maximize thermal efficiency, while minimizing pollutant emissions.

One aspect of this combustion process that differs from nearly all other types of industrial combustion processes is the varying fuel composition. In most cases, the fuels used in process heaters in refineries and chemical plants are waste gases generated during the production of liquid fuels such as gasoline and chemicals such as ethylene. These waste gases may consist of a dozen or more components and usually contain significant amounts of methane (CH_4), propane (C_3H_8), hydrogen (H_2). Further complicating the situation is that different fuels may be used in a given heater depending on the type of operation and on the products being made in the plant at the time. For example, natural gas may be used during startup until enough refinery gas is produced to fuel the heaters. One normal operation fuel may contain very little H_2, while another normal operation fuel may have very high concentrations of H_2. Fuel composition has a significant impact on burner design and performance.

Since most process heaters are natural draft, there is not a convenient way to directly measure the combustion air flow rate. Instead, the amount of O_2 in the exhaust gases, termed the excess O_2, is measured and then the air flow rate is calculated. Excess O_2 levels must be closely controlled to ensure safe operations, maximize thermal efficiency and productivity, and minimize pollution emissions. Figure 2 shows how available heat varies with excess air based on theoretical equilibrium calculations for ambient air reacting with 100% methane. The exhaust products are assumed to be at 2000°F. Available heat is defined as the energy in the fuel gas minus the energy in the exhaust products leaving the combustor. Although not all of the available energy actually goes into the process as some of it is lost (e.g., conduction through the furnace walls), it is closely related to thermal efficiency.

In Figure 2, the thermal efficiency decreases when excess air increases above 0%. This decrease occurs because of the added heat load from the extra O_2 and N_2 in the air that absorbs heat which is carried out with the flue gases. The thermal efficiency decreases when the "excess" is below 0%. This decrease occurs because there is insufficient oxygen to completely combust all of the fuel, which means that not all of the chemical energy is converted into thermal energy. Insufficient air is also potentially unsafe because the unburned fuel could be ignited somewhere else inside of the heater. For example if tramp air is leaking into the convection section, the unburned fuel could mix with that air, which could lead to burning in the convection section or to an explosion. Note that although the maximum available heat is at 0% excess air, heaters are normally operated with some amount of excess air for safety reasons to ensure there is sufficient O_2 to fully combust the fuel.

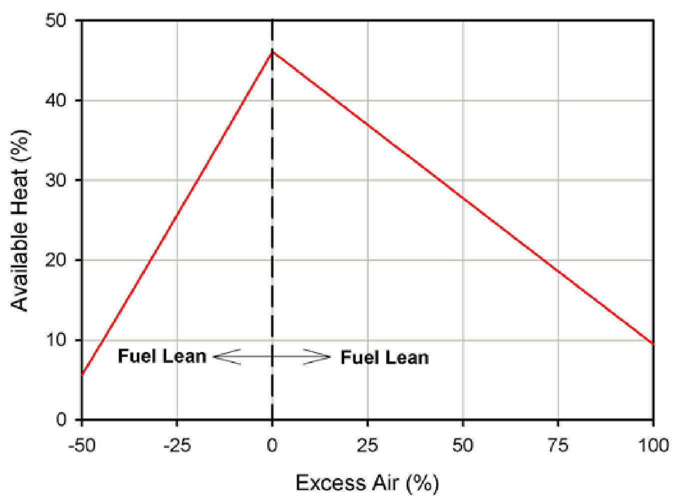


Figure 2.   Available heat vs. excess O_2 for methane combusted with ambient air (2000°F flue gas temperature).

The two most common pollutants regulated in process heaters are carbon monoxide (CO) and nitrogen oxides (NOx).[1] These pollutants are sensitive to the amount of excess O_2. Figure 3 shows that with increasing excess air levels above 0%, the CO decreases and NOx increases. Ideally, the goal is to minimize both pollutants, which can be challenging since each reacts oppositely to excess air levels. Ultra low NOx burners use a variety of strategies to minimize both pollutants.[2] High levels of CO indicate incomplete combustion and improper burner operation. High NOx emissions are a problem if they exceed permitted limits. Therefore, heater O_2 levels are typically controlled as low as possible, without forming high levels of CO, to maximize thermal efficiency and minimize NOx emissions. For safety reasons, a manually-operated heater is operated with some excess O_2. Variations in ambient air (e.g., temperature and humidity), fuel (e.g., temperature and composition), and process operating conditions (e.g., process fluid flow rate) can cause excess O_2 to fall below acceptable levels. For this reason, O_2 is closely monitored.

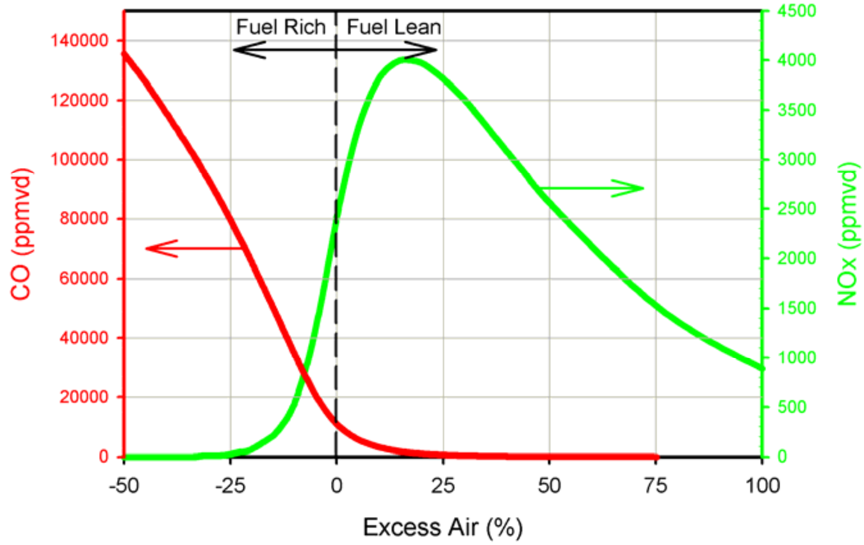


Figure 3. NOx and CO vs. excess O_2 for methane combusted with ambient air.

Heat Transfer

Heat transfer in a heater is critical to proper operation. The bulk of the heat transfer in the radiant section is by radiation, hence the name *radiant section*. The bulk of the heat transfer in the convection section is by convection, hence the name *convection section*. Conduction losses through the heater walls reduce the thermal efficiency. The heat flux pattern inside the heater from the burners is also a critical parameter. Too much heat in a localized area can cause damage. Flame impingement on process tubes can cause the hydrocarbon fluids to form coke layers inside the tubes. These layers reduce the heat transfer through the tubes which causes the tubes to overheat and can ultimately lead to a rupture. Ruptured process tubes allow hydrocarbon fluids to flow into a hot heater and are potentially very dangerous as they can cause very large fires. Engineers need to know the basic principles of heat transfer in a heater to maximize performance.

Fluid Flow

Most process heaters are natural draft, which means no fans or blowers are used to supply the combustion air to the burners or remove the combustion products from the heaters. Heater draft refers to the negative pressure that develops when hot gases rise inside the heater. Draft pulls in the air needed for combustion and pushes out the products of combustion such as CO_2, H_2O, O_2 and N_2. Ideally, the excess O_2 should come from the air being pulled through the burners, although some also comes from air leaking into the heater through cracks and openings, which is called *tramp air*.

Figure 4 shows burners firing across the floor from both sides of a process heater. The figure on the left shows the heater before the O_2 and draft were properly adjusted. Notice how ill-defined the flames are and how relatively cold the heater is because of incomplete combustion. The figure on the right shows the flames after the O_2 and draft have been properly adjusted. The fuel composition and firing rates are essentially the same in both cases. The flames in the right photo are now well-defined and the heater is hotter which means more throughput of hydrocarbon fluids. These photos in Figure 4 show how proper adjustments improve flame quality.

(a) (b)

Figure 4. (a) Before and (b) after adjusting the O_2 and draft in a process heater.

An operator can control the heater draft and excess O_2 by adjusting the damper on the heater exhaust stack, referred to as the stack damper, and on each burner, referred to as the burner damper. Although both the stack and burner dampers impact the draft and O_2, the stack damper should be primarily used to control the heater draft while the burner dampers should be primarily used to control the excess O_2 in the heater.

Heater Simulator

Figure 5 shows an example screen from an electronic heater simulator that was developed primarily as a teaching tool. The simulator has numerous inputs that can be varied to demonstrate the effects of a variety of parameters related to fluid flow, heat transfer, thermal efficiency, pollution emissions, and operating conditions. The simulator is semi-analytical as most of the calculations are based on well-known physics. There are also some empirical equations built into the model to calculate, for example, NOx emissions from a wide range of burner types.

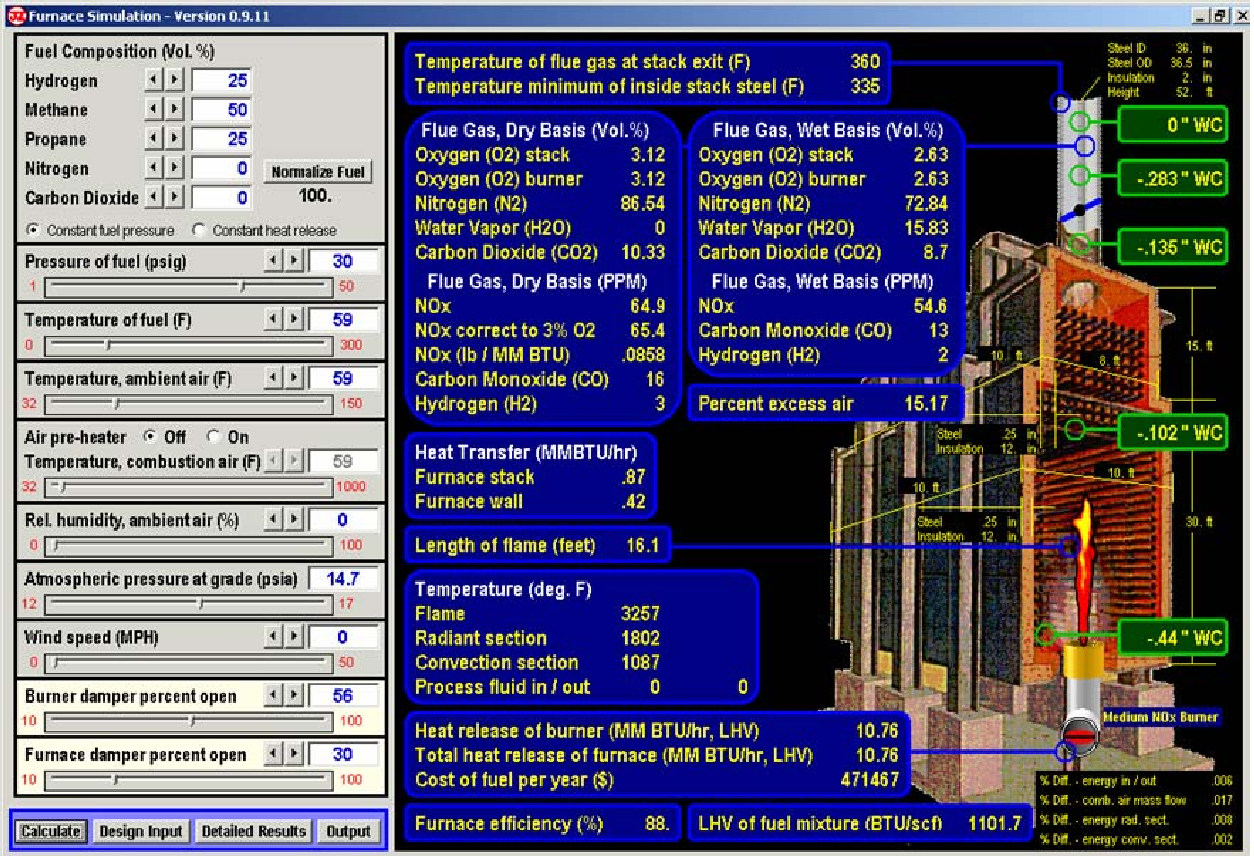
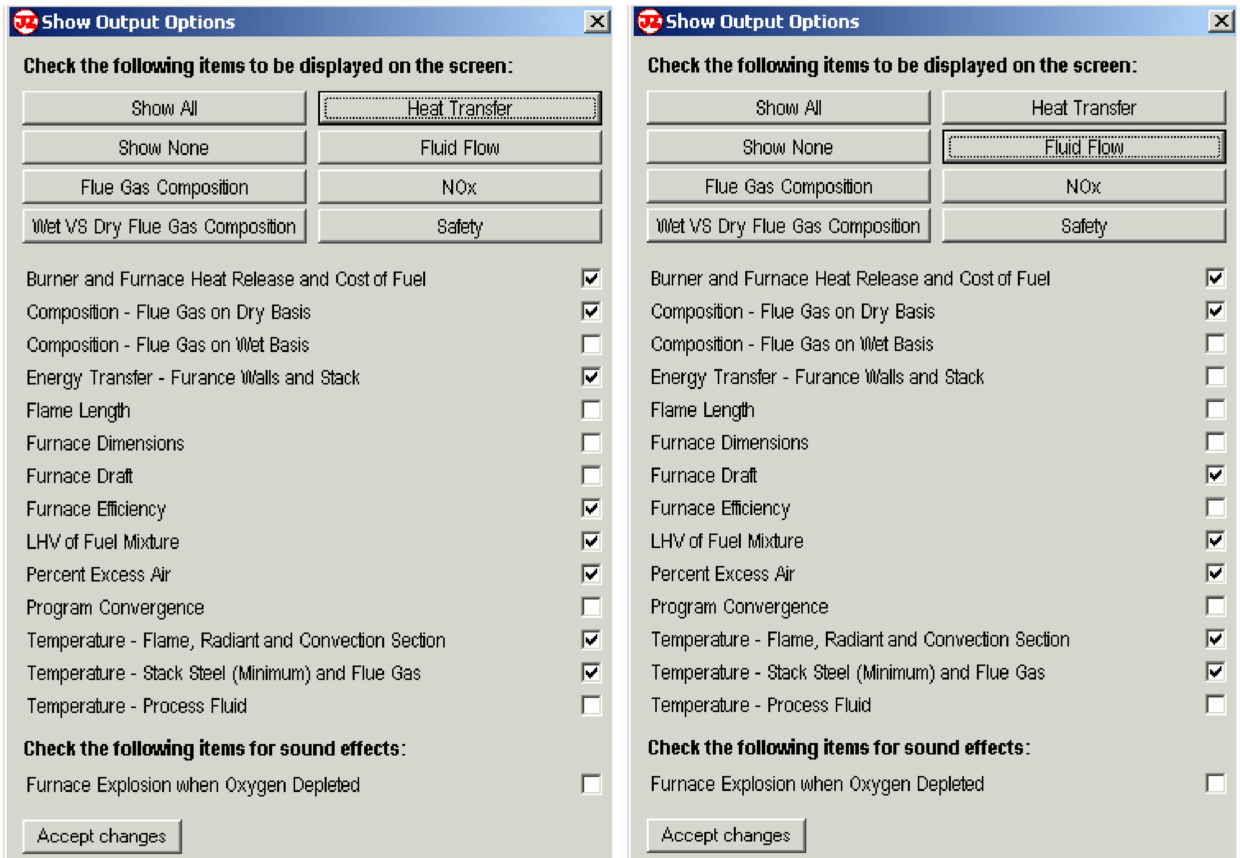


Figure 5. Example screen from heater simulator.

The primary inputs are shown on the left in Figure 5. Many other more detailed inputs can be modified on a secondary screen. Those inputs are not typically adjusted in the classroom because they do not directly concern the principles being taught with the simulator and would take valuable time to explain. Some of the secondary inputs include design information on the burner, the radiant and convection sections in the heater, and the process fluid.

There are also numerous outputs. The example shown is for a simulated refinery fuel consisting of 50% CH_4, 25% C_3H_8, and 25% H_2 at 30 psig supply pressure combusted with ambient air. The burner and stack dampers were adjusted to 56% and 30% open respectively so the excess O_2 and draft at the top of the radiant section were approximately 3% (dry basis) and -0.1" water column, respectively. These are common operating conditions for these heaters. Students see how both variables are affected by changes in the positions of those dampers, since those are the primary adjustments made by the heater operators. If the O_2 level gets too low, a warning appears on the screen stating that the heater is running out of air.

Displaying all outputs as shown in Figure 5 is too busy for instructional purposes, so a reduced set of outputs are available depending on what principle is being discussed. Figure 6 shows two examples of screens used to control the outputs. The instructor can individually check boxes to see specific outputs, or can select categories at the top of the screen to make the selection process faster and easier. The left and right figures show which outputs are displayed when the "Heat Transfer" and "Fluid Flow" categories are selected, respectively.



(a) (b)

Figure 6. Screen for controlling outputs displayed on main screen: (a) heat transfer outputs and (b) fluid flow outputs.

<u>Combustion</u>

There are several parameters of particular interest in heater operation related to combustion. One is the excess O_2 level which is an indicator of thermal efficiency as shown in Figure 2 and pollution emissions as shown in Figure 3. Other combustion parameters of great importance are CO and NOx emissions. O_2, CO, and NOx are all part of the combustion products in the exhaust gas. Figure 7 shows the predicted combustion products on both a wet and dry basis, where the water has been removed in the latter case. These two bases are displayed because flue gas analyzers used in plants may report on either a wet or dry basis.

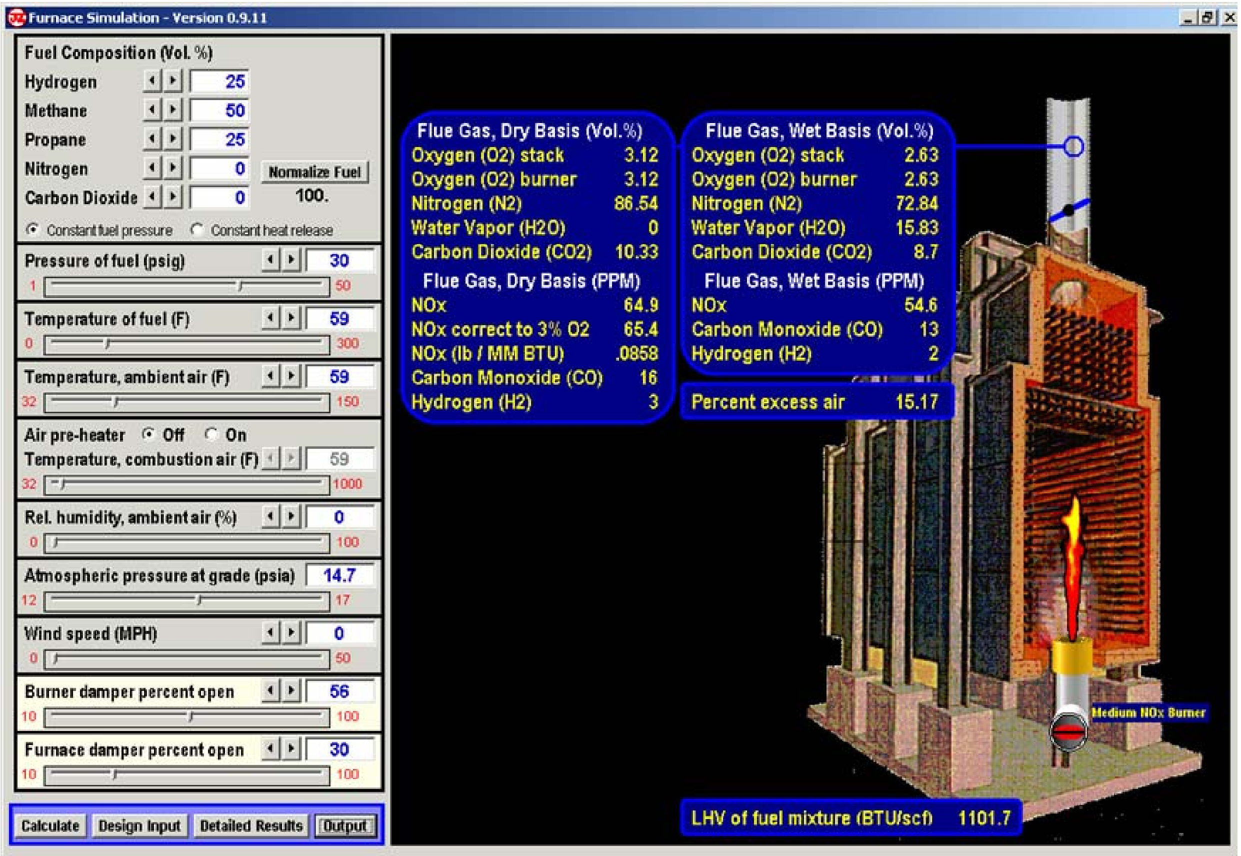


Figure 7. Flue gas composition predictions.

Heat Transfer

Figure 8 shows predicted heat transfer parameters for the sample case being considered here. Some of these parameters include the heat lost through the heater walls, the heat lost out the stack, the overall heater efficiency, and some selected temperatures. Engineers and operators can see what happens, for example, to the heater efficiency as important parameters such as excess O_2 are varied. Although it is not the normal instructional purpose of the simulator, it can be used to vary burner and heater design parameters to study the effects on heat transfer.

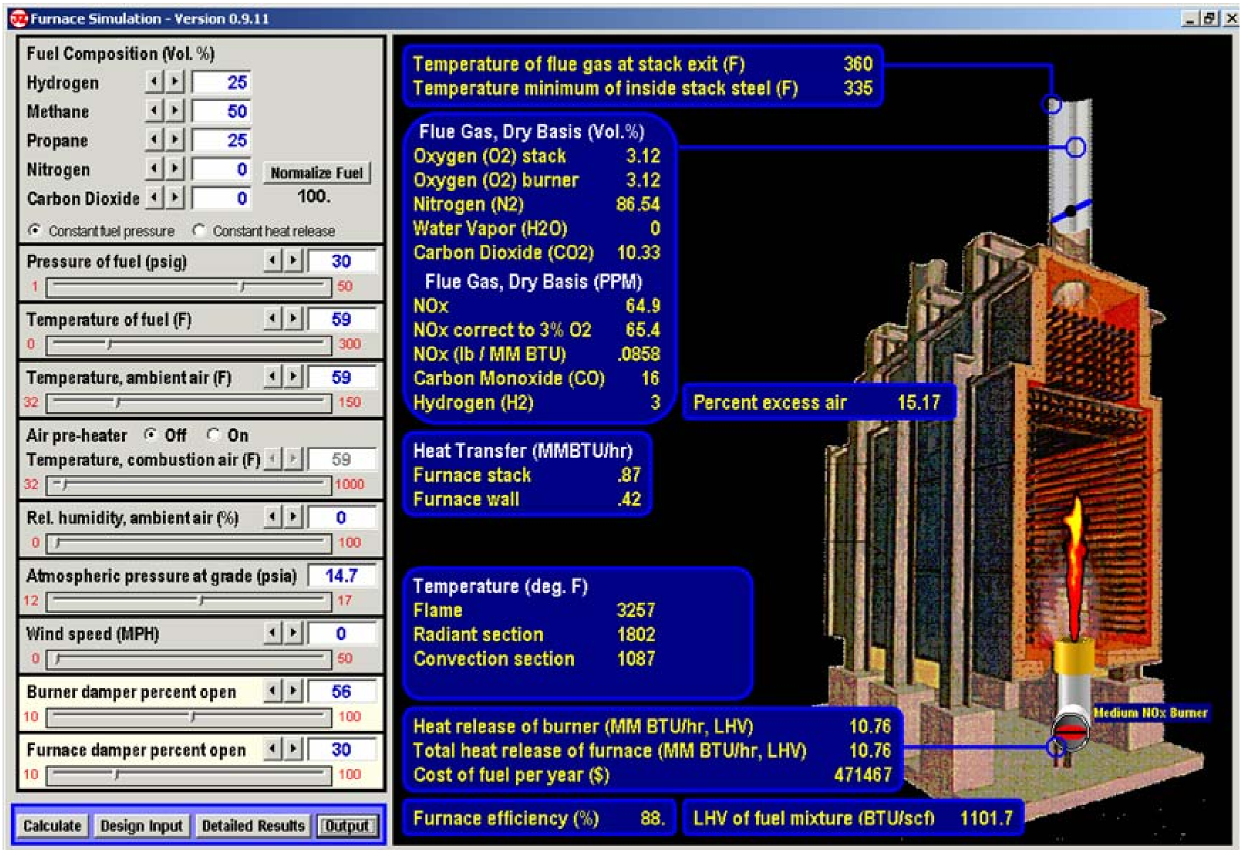


Figure 8. Heat transfer predictions.

Fluid Flow

Figure 9 shows the various predicted draft levels inside the sample case heater. The two most important levels are at the top of the radiant section and at the heater floor level. Process heaters are typically designed where the former is at approximately -0.1 inches of water column. This is the least amount of suction inside the heater. The draft is designed to be slightly negative there so no flue gases leak from the furnace. If flue gases do leak out there, heater damage often results as well as the potential exposure of hot flue gas to personnel working nearby. The draft level at the floor is critical for properly sizing the burners to get the necessary combustion air flow based on the available pressure drop.

Figure 10 shows the predicted draft levels inside a heater using the simulator. The green line shows the design conditions, while the red and blue lines show high and low draft conditions, respectively. If the draft is too high, then too much tramp air will be pulled into the heater which can reduce efficiency or cause poor burner operation because the correct amount of air is not coming through the burners. If the draft is too low, then hot gases can leak out of the heater with the problems previously discussed.

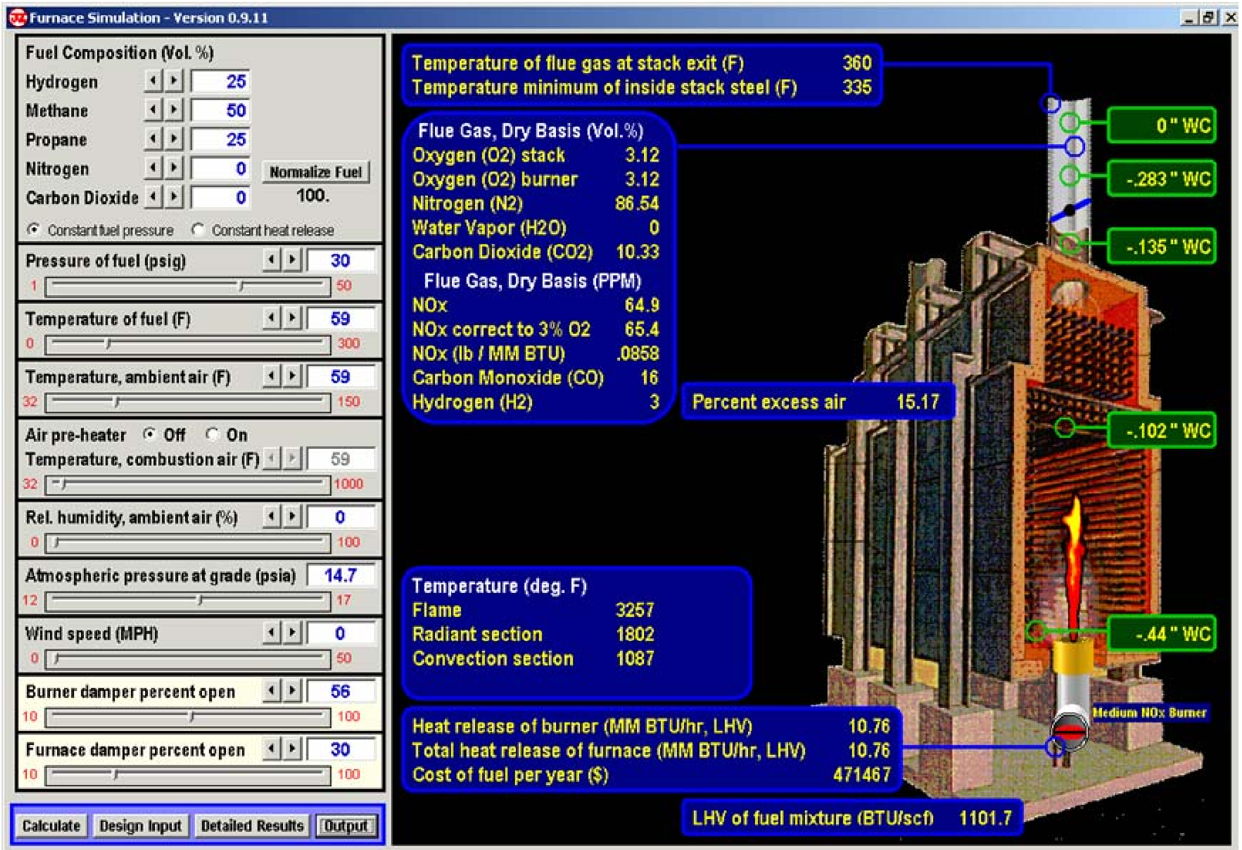


Figure 9. Fluid flow predictions.

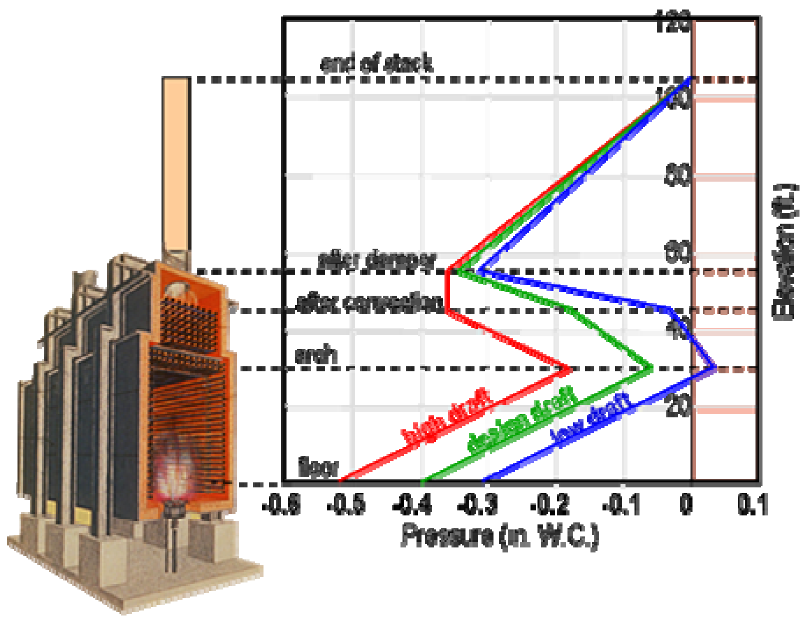


Figure 10. Draft variation with elevation in a process heater.

Conclusions

Using a simulator is not only safer than making adjustments on an operating heater, it is also much faster and easier for instructional purposes. Real heaters take some time to react to changes in damper positions where the simulator reacts immediately. Also, noise levels are often high around operating heaters making it difficult to communicate with a group of students, which is not the case using a simulator in a classroom.

Some important principles that need to be taught related to process heater operation include combustion, heat transfer, and fluid flow. Excess O_2, CO and NOx are important combustion parameters. Heat losses and overall furnace efficiency are important heat transfer parameters. Draft is the primary fluid flow parameter of interest in process heaters. An electronic simulator has been developed to teach and demonstrate these principles in continuing engineering education courses.

References

1. Baukal, C., *Industrial Combustion Pollution and Control*, New York: Marcel Dekker, 2004.
2. Baukal, C. (ed.), *Industrial Burners Handbook*, Boca Raton, FL: CRC Press, 2004.