SOFTWARE TOOL OPTIMIZES

FURNACE DESIGN AND OPERATION

Adapted from an article published in the **November 2002** issue of **Heat Treating Progress**.

This PC-based software program can help furnace builders reduce the time needed to design and size a furnace, while heat treaters can use it to determine the optimum setup for any furnace/part combination.

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The task of designing and analyzing industrial furnaces is complex and time-consuming. Most furnaces are not mass-produced but built to specification. During the proposal phase of furnace buying, the customer's needs are communicated to the furnace manufacturer, who, in turn, comes up with several design solutions to satisfy these requirements. This process usually involves several iterations of lengthy engineering calculations.

One of the key aspects of furnace sizing and design is the need to understand the heat transfer among furnace walls, furnace atmosphere, and the parts being heat treated. It's well-known that heat flows from higher temperatures to lower temperatures, and that heat transfer takes place by radiation, convection, and heat flux. However, determination of each of these heat transfer components involves

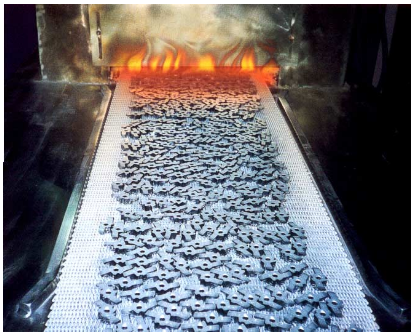

Fig. 1 — Entry end of a Sinterite continuous mesh belt sintering furnace similar to the one used for the simulation described in this article. Courtesy Sinterite Furnace Div., Gasbarre Products Inc.

complex calculations. For example, at high temperatures, heat transfer takes place by radiation. Unfortunately, it is not a linear function. Moreover, thermophysical properties change with temperature. Engineers and designers use rules of thumb and manual calculations to "solve" these complex problems. Some may even use a computer spreadsheet program. The fact is that meaningful solutions to these problems cannot be obtained by manual or simple spreadsheet means.

The same argument applies to furnace users. Process engineers and heat treaters are always faced with the challenge of operating their furnaces at the highest efficiency without sacrificing product quality. With every new part to be processed comes the challenge of determining optimum furnace settings. The common practice is to develop process parameters via pilot runs (test bakes), but pilot runs tie up production, build work-in-process (WIP) inventory, produce scrap, waste resources, and often do not yield the best results.

Enabling technology: Thanks to advances in computer technology, the barriers formerly posed by these challenges have been leveled. More and more engineers are now using software tools for accurate analysis and simulation of equipment and processes. Moreover, the software provides a window on the process, enabling engineers to better understand what happens inside the parts as they are heat treated.

This article focuses on computer software that functions as a furnace design and setup tool. Furnace manufacturers can use the FurnXpert program to accurately and efficiently size furnaces for their customers, while heat treaters, process engineers, and plant operators can use the design and analysis software to determine the best setup for any furnace/part combination.

Sintering furnace case study

To help illustrate the benefits of design software, an analysis of a furnace was performed first using manual calculations and then using FurnXpert software. The results were then compared.

Although FurnXpert software can be used to analyze any type of batch or continuous furnace, the subject of this study was a continuous mesh-belt furnace for sintering powder metallurgy (P/M) parts (Fig. 1). The furnace had a belt width of 18 in. (46 cm) and was configured as follows:

Furnace Power Systems Analysis

Customer:	Example							
Job:	N/A							
Furnance Type:	18E-5Z					Target Output:	545	Lb/hr
Belt Width:	18	inches				Calculated Output:	548	Lb/hr
Belt Type:	314ss					Process Gas:	1280	CFH
Belt Weight:	5	Lb/ft2	Belt Load:	270	Lb/hr	Cover Gas:	(see Proc.)	CFH
Belt Cp:	0.12	Btu/Lb-F	Belt Mat'l:					
Part Loading:	10.15	Lb/ft2	Part Load:	548	Lb/hr			
Part Cp:	0.12	Btu/Lb-F	Part Mat'l:		k33+0			
Tray Weight:		Lb/ft2	Tray Load:		Lb/hr			
Tray Cp:		Btu/Lb-F	Tray Mat'l:			Total Output:	818	Lb/hr
Process Speed:	7.2	in/min						

Insulation Thermal Data:

	9"	12"
Temp F	HL-HS	HL-HS
1000	49-757	37-986
1200	75-951	57-1235
1600	151-1374	113-1773
1800	202-1603	152-2062
2100	346-2039	260-2590

Btu/H - KW 2.93E-04

Gas Data:

Gas	Cp	Lb/ft^3
Air	0.24	0.076
AR	0.124	0.103
CH4	0.593	0.045
H2	3.43	0.0056
N2	0.249	0.075
NH4	0.523	0.044

Furnace Configuration:

					Percent of Process					Insulation Configure					
	Zone #	Zone Len	Ovall Length	Peak Temp.	St @ Temp	Fn @ Temp	Time @ Temp. (min.)	Ent Temp	Exit Temp	Ins. Width	Ins. Height	Thk.	Type	HL (Btu/ft2/hr)	HS (Btu-ft2)
Delube	1	72	72	1200	75	100	2.5	200	1300	29	25	12	Fiber	113	1773
Preheat	1	72	72	1800	95	100	0.1	1300	1800	29	25	12	Fiber	152	2062
HighHeat	3	60	180	2050	15	85	15	1800	1800	29	25	12	Fiber	260	2590

Atmosphere Gas System:

Zone	Type	Cp	Lb/ft^3	Vol (CFH)	dTemp	Btu/H	Kw
Delube	N2	0.249	0.075	350	300	1960.87	0.57
Preheat							
High Heat	H2	3.43	0.0056	15	1500	432.18	0.13
High Heat	N2	0.249	0.075	1165	1500	32634.56	9.56
Side Cover	N2	0.249	0.075	100	1500	2801.25	0.82
exit	N2	0.249	0.075	50	300	280.13	0.08
					Subtotal:	38108.99	11.16

HEAT LOSS ENERGY ANALYSIS:

Process	Surf Area (Ft^2)	Tot Loss (Btu/Hr)	KW
Delube	5.03	568.93	0.17
Preheat	59.03	8973.27	2.63
High Heat	59.03	15349.03	4.50
	Subtotal	24891.23	7.30

Ramping Power Requirement:

Process	dTemp / dtime	Rate (Hr)	Time in Zone (min)	Btu/H	Kw
Delube	1000	0.125	0.17	130897.05	38.36
Preheat	500	0.165	0.17	49582.21	14.53
HighHeat	400	0.05	0.14	109080.87	31.97
		Subtotal		289560.13	84.86
				Atmosphere Power	11.16
				Heat Loss Power	7.30
				Total	103.32

Zone	Power Consumption	Installed Power
1	50.98	55
2	16.56	55
3	33.43	55
4	4.25	55
5	41.80	55
Total	147.02	275

Fig. 2 — Manual methods have traditionally been used to design and analyze furnaces. The trend is to use spreadsheet software. Time is saved, but the underlying calculations are the same.

- Five heating zones: delube zone, 72 in. (1.8 m) long; oxide reduction zone, 72 in. (1.8 m) long; three sintering zones, each 60 in. (1.5 m) long.
- Three cooling zones: fast cooling zone, 48 in. (1.2 m) long; two slow cooling zones, each 120 in. (3 m) long.

Example of manual method

For a long time engineers have used manual calculations to design and analyze furnaces. The trend today is to use spreadsheet computer software. Time is saved but the underlying calculations are the same.

Both manual and spreadsheet calculations start with certain assumptions or inputs. In this sintering furnace example, the manual calculation is based on the specification that the part loading capacity is 10.15 lb/ft^2 (49.6 kg/m^2) and that parts will be sintered for 16.25 minutes at temperature. The balance of the calculations involves determining the power requirements in each of the furnace zones by analyzing the heat input to the parts, heat input to the conveyor belt, heat losses through the refractory, and heat input to the process gas. The calculations follow:

- First, determine the production speed empirically: Production speed (in./min) = Sintering zone length (in.) $\times$ Heating zone efficiency/Time at temperature (min) = 180 $\times$ 0.65/16.25 = 7.2 in./min.
- Next, calculate the production rate using this equation: Production rate (lb/h) = Load capacity (lb/ft^2) $\times$ Load width (ft) $\times$ Production speed (ft/h) = 10.15 $\times$ 1.5 $\times$ (7.2 $\times$ 60/12) = 548.1 lb/h.

From the available data, the calculated production speed and production rate are 7.2 in./min (18 cm/min) and 548 lb/h (250 kg/h), respectively. The rest of the manual calculations are shown in the Microsoft Excel spreadsheet screen in Fig. 2.

Design and analysis tool

FurnXpert simplifies the job of sizing, designing, and simulating furnaces used for heat treating metal parts. Running the software involves three main steps.

1. Specify a furnace, including physical dimensions, refractory type, thermocouple locations, and type of heating (electric or gas).
2. Select parts to be processed in the furnace. Specify part shape, size, material, and configuration.
3. Specify furnace settings. These might include zone temperatures or the temperature profile along the length of the furnace, atmospheric gas flow, production speed, and furnace pressure.

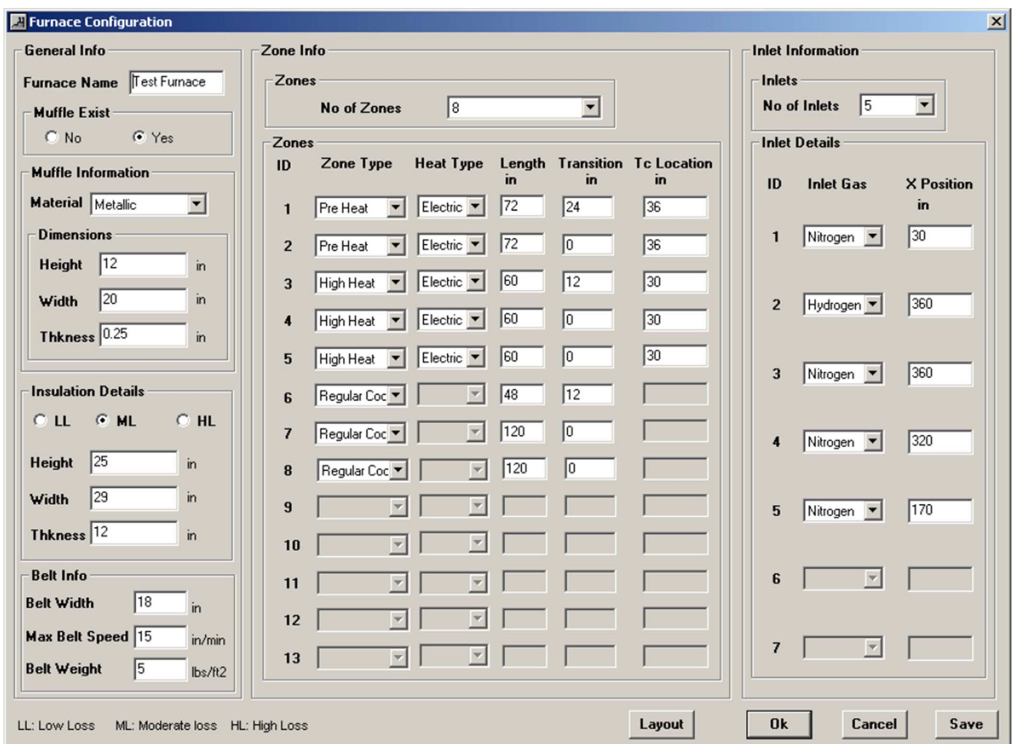

Fig. 3 — FurnXpert's "furnace configurator" lets the user specify the furnace to be analyzed. This screen shows the parameters for the sintering furnace featured in this case study.

With these inputs, the software program can generate information such as temperature change inside the part with time or at different locations in the furnace. Since the properties inside a part are directly related to the temperature, the determination of part temperature is a critical step in controlling the heat treating process. For furnace designers, the software also calculates various heat losses, heat requirements for the parts, and overall furnace efficiency.

To draw a comparison between manual calculations and FurnXpert, the software program was used to analyze the same sintering furnace. The six steps needed to perform the computer analysis are:

- Configure furnace
- Create part
- Select part for simulation
- Place parts
- Select settings
- Run simulation

Configure furnace: The "furnace configurator" feature lets the user specify the furnace to be analyzed. The parameters required to configure a furnace are: zone types; zone lengths; thermocouple locations; insulation type, dimension, and thickness; muffle type (if applicable) and dimensions; belt width and weight; and process gas inlet location.

The FurnXpert screen in Fig. 3 shows the parameter inputs for the sintering furnace that was the subject of this case study.

Create part: Any type of part can be configured with FurnXpert. There are seven shapes from which to choose (Fig. 4). After selecting a shape, the user enters its dimensions and picks the material from a pull-down list. The newly created part is then saved in the database with a unique name, and can be recalled via the "select part" option.

Select part: Any part that has been created can be selected to run the simulation. This is a powerful feature, because it not only enables the user to simulate the design part, but also allows "what if" analyses of other parts to determine whether they could be heat treated in the same furnace. Figure 5 shows the "select part" screen for the previously created P/M steel bushing (Fig. 4).

Place parts: Once a part has been selected to process in the furnace, the part placement configuration must be specified. The screen shot in Fig. 6 shows the available configurations. The user can run furnace simulations using different part orientations to determine the effects of part placement on furnace design and performance.

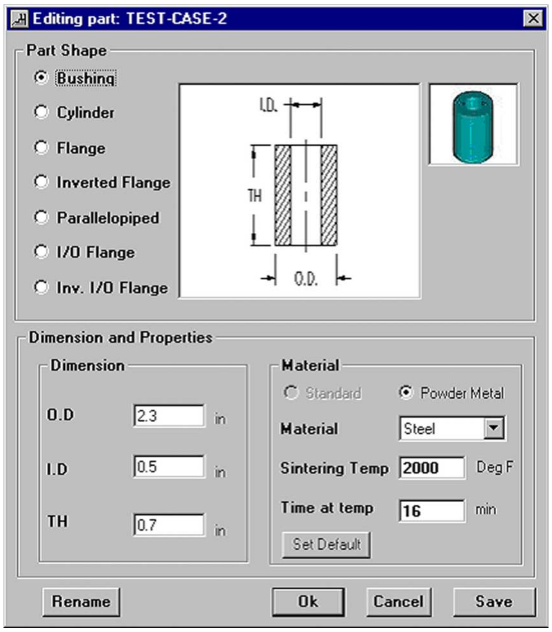

Fig. 4 — Any type of part can be configured or "created" with FurnXpert. After selecting one of seven basic shapes, the user enters its dimensions and picks a material from a pull-down list.

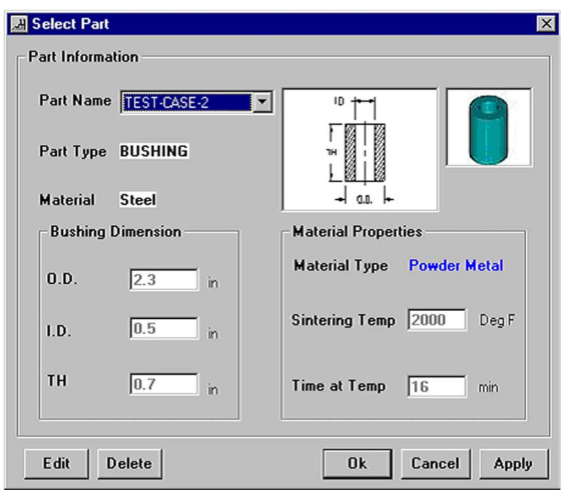

Fig. 5 — The "select part for simulation" screen for the previously created P/M steel bushing (Fig. 4). Other parts also can be analyzed to see if they could be processed in the same furnace.

Select settings: The user then selects the furnace settings (Fig. 7). This feature enables the effects of different settings on parts and furnace to be assessed. In this example, the settings are temperature, process gas flows, and belt speed. (Note that a temperature vs. distance profile can be selected instead of temperature setpoints.)

Run simulation: The analysis can be run after furnace parameters, part parameters, and operating conditions have been chosen. The analysis includes two steps. In the first, the software uses the finite element method to calculate the temperature of the part at every point along the length of the furnace (the red line in Fig. 8).

The finite element method is a mathematical technique of breaking down a part into small elements and calculating the temperature for each individual element. So at every calculation step, the model simultaneously determines the temperature at several points on or in the part. The model uses the furnace temperature profile as the boundary condition (the blue line in Fig. 8). The profile is determined from the temperature settings for each zone (yellow inverted triangles).

In the second step, the software performs the heat loss calculations required to determine heat gained by the parts, belt, trays, and process gases, and heat lost through the insulation. These data are then consolidated to calculate the power requirement for each zone of the furnace (Fig. 9).

How results compare

The results of the FurnXpert analysis are compared with those derived by manual or spreadsheet calculation in Table 1. Although the results from the manual calculation come quite close to the FurnXpert results, there are some noticeable differences that require explanation.

Heat transfer: Manual calculations are based on certain assumptions, which may impose limitations. For example, it was assumed that the part would reach a certain temperature at a certain location inside the furnace. Input for the manual calculations was obtained from the temperature vs. distance profile shown in Fig. 10.

However, the actual temperature attained by a part depends on many factors. First, the mode of heat transfer at low temperature is different from that at high temperature. Convection plays a dominant role at low temperature, and the convective heat transfer coefficient depends on the atmosphere present inside the chamber and flow characteristics around the body. On the other hand, heat transfer takes place by radiation at high temperature, and it is a nonlinear function of temperature. Moreover, the amount of heat transfer by radiation depends on the "view factor" between the two bodies exchanging heat — any shadowing effect can significantly affect heat transfer. Therefore, understanding and solving the physics of heat transfer between the furnace and the parts being heat treated is the crucial step in designing, simulating, and analyzing a furnace. These effects are deliberately ignored in manual calculations because it is impractical to account for them.

Rules of thumb: Next, some of the manual calculations are based on rules of thumb and empirical values. For example, the belt speed of 7.2 in./min is calculated on the assumption that the part is exposed for 16.25 minutes at sintering temperature for 65% of the sintering zone. This is not true, because parts of different size and shape will have a different temperature profile and, consequently, a different time at sintering temperature.

Heat lost to refractories is a function of the temperature of the refractory. Losses at higher zone temperatures are greater than those at lower temperatures. The manual calculations assume that refractory temperature is the same as part temperature. This is not thermodynamically accurate — heat flows from the furnace wall to the part, which is at a lower temperature.

Solutions: All of these issues are addressed in FurnXpert. For example,

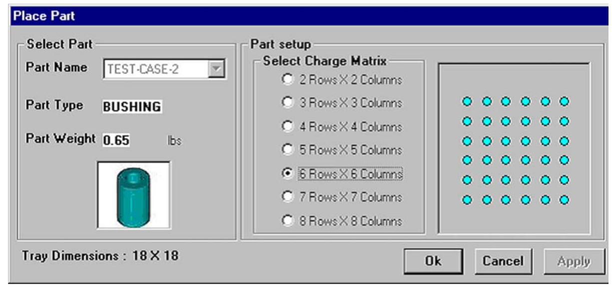

Fig. 6 — How parts are loaded on the belt also is specified. Simulations using different part placements can be run to determine their effects on furnace design and performance.

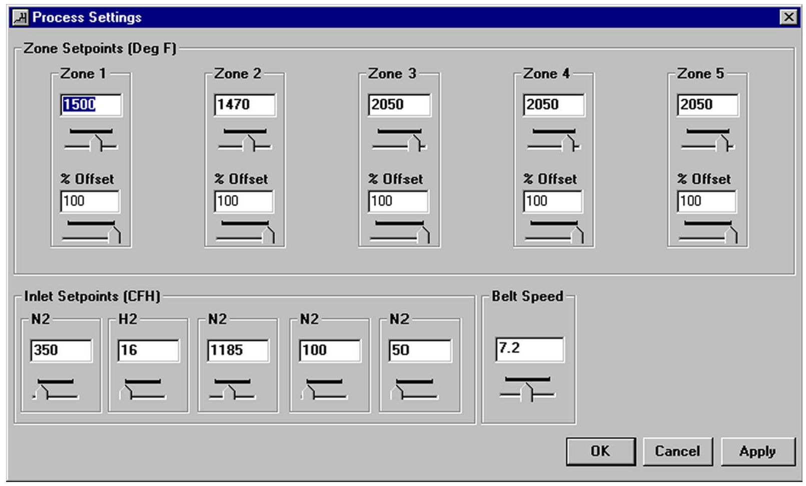

Fig. 7 — The user selects the furnace settings: temperatures, process gas flows, and belt speed in this case. (Note: A temperature vs. distance profile instead of setpoints can be chosen.)

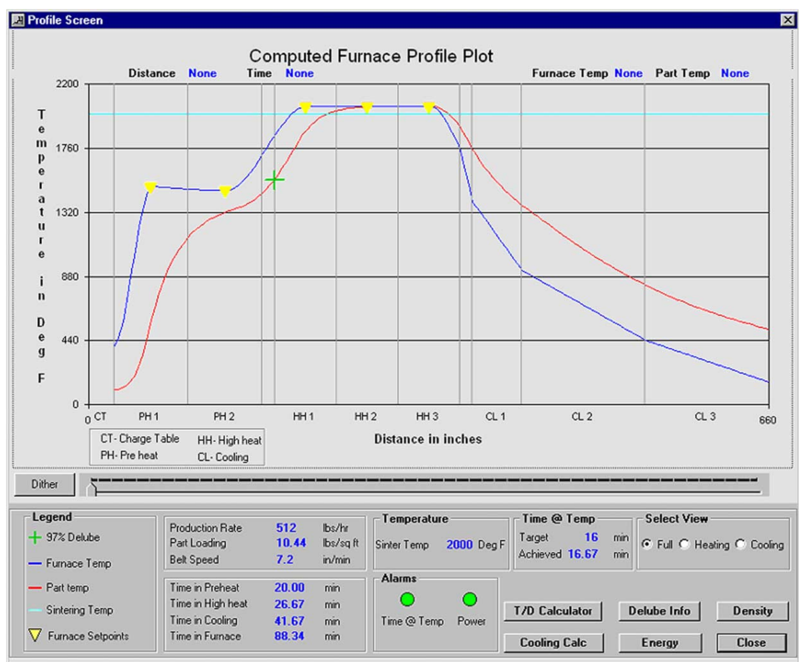

Fig. 8 — A FurnXpert simulation uses the finite element method to calculate the temperature of the part at every point along the length of the furnace (red line). The model uses the furnace temperature profile as the boundary condition (blue line). The profile is determined from the temperature settings for each zone (yellow inverted triangles).

calculations are based on zone temperatures. Once the user provides zone temperatures, the program uses an algorithm to calculate the furnace temperature profile during the heat treating process. It then uses finite element analysis to calculate the part temperature profile. Other factors contributing to the differences in results are:

- The manually calculated production rate assumes that parts are uniformly loaded on the belt. FurnXpert calculates production rates from part weight and their placement on the belt
- Radiation heat loss from the last heating zone to the cooling zone is not accounted for in the manual method. It is combined with the heat to the part (as indicated in Table 1).

Zone Heat Details

Zone Heat Details(kW)

Zone	Heat to Part	Wall Loss	Heat to Gas	Heat to Belt	Radiation Loss	Total Heat
Zone 1	22.84	2.16	2.74	10.10	0.00	37.85
Zone 2	10.19	2.90	0.38	2.86	0.00	16.33
Zone 3	14.03	3.73	0.54	5.27	0.00	23.57
Zone 4	0.57	3.70	0.00	0.25	0.00	4.52
Zone 5	0.01	2.77	14.10	0.00	22.00	38.88
Total Heat	47.64	15.27	17.76	18.49	22.00	121.15

Total Power 121.15 kW Energy Con. 0.23649 kW-hour/lb

Close

Fig. 9 — The simulation software also performs a variety of heat loss calculations. These data are then used to calculate the power requirement for each zone of the furnace.

Attention to detail needed

Heat transfer calculations are complex and tedious. Performing them in detail either manually or even with the help of a spreadsheet program is impractical. However, these details can make a significant difference in overall furnace design and cannot be ignored.

Accuracy in manual calculations depends on rules of thumb and empirical values. Manual calculations can provide accurate results if the empirical values used are on target. This is only possible if these values are calibrated properly by comparing the results of manual calculations with experimental results. Even so, the empirical values can only be used with the furnace for which they were developed.

Computer Software Vs. manual sintering furnace simulation

Result	FurnXpert	Manual or spreadsheet
Production rate, lb/h	512	548
Part loading, lb/ft^2	10.44	10.15
Time in preheat, min	20	20
Time in sintering, min	26.67	25
Zone 1 power, kW	37.85	50.29
Zone 2 power, kW	16.33	16.54
Zone 3 power, kW	23.57	33.43
Zone 4 power, kW	4.52	4.25
Zone 5 power, kW	38.88	41.80
Wall heat loss, kW	15.27	7.30
Atmosphere heating, kW	17.76	11.16
Heat to part, kW	66.13	84.86
Radiation loss, kW	22.00	Not accounted for

Advantages: The primary benefits of using a software tool like FurnXpert is that it can perform a furnace simulation 10 times faster and with much greater accuracy than manual methods. In addition, the software also presents an overall picture of the process. The factors that contribute to achieving accurate results are:

- Calculations are based on furnace temperature and not on a predicted part temperature.
- Property changes (thermal conductivity, density, and specific heat) with temperature are accounted for at each calculation step.
- All heat transfer modes are considered and solved at each calculation step.
- Use of the finite element method analyzes every detail of the part.

Finally, the process of design and analysis of a furnace or furnace operation involves running a series of cases. Each case would involve a different combination of furnace design, part parameters, and furnace settings. With a program like FurnXpert, these different cases or "what if" analyses can be run in a fraction of the time it takes to perform them manually. This not only makes the design process more efficient, but also gives more accurate results and ultimately a better product or process.

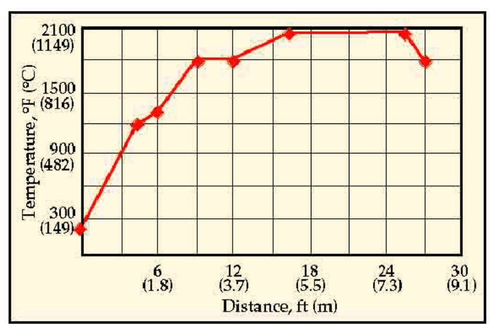

Fig 10 — Input for the manual calculations was obtained from this furnace temperature vs. distance profile, which may not accurately reflect part temperature.

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