8.1 IR Furnace Process

The infrared furnace continuously processes product on a moving belt. Each product moves through the same areas and is exposed to the same process elements. The furnace process sections are shown in Figure 8-1.

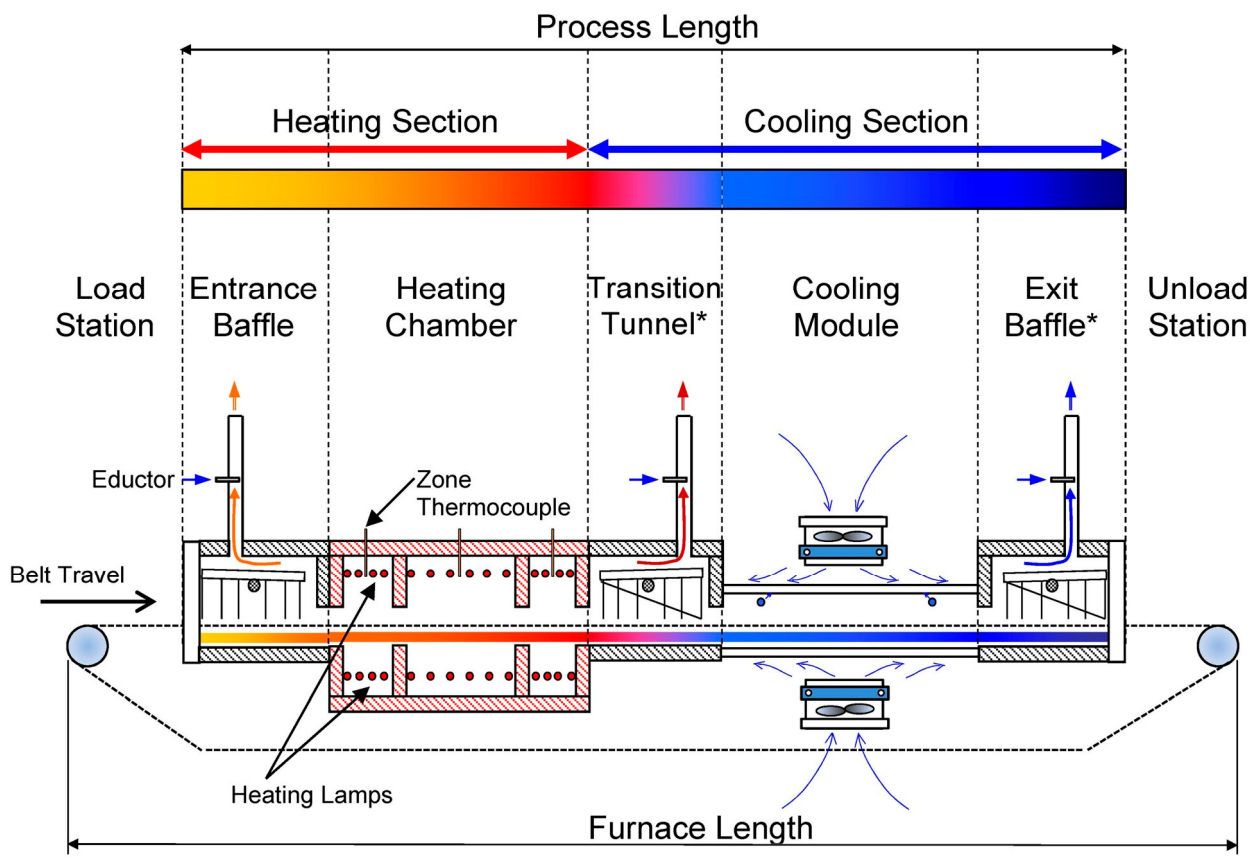


Figure 8-1 IR Furnace Process Sections

*Furnace configurations vary. Some furnaces are not equipped with a stack on the Transition Tunnel or an Exit Baffle.

Continuous IR Processing is generally characterized by rapid ramping rates, ability to vary temperatures greatly from zone to zone and consistent processing performance in a controlled atmosphere. Establishing an acceptable profile and stabilizing the furnace are key to successful thermal processing. This is done by managing the following:

- Zone Temperatures
- Belt Speed
- Process Gas inflow
- Balancing the Gas flow using exhaust venturi flow
- PID Loop and Zone Power adjustments

8.1.1 Zone Temperatures

Set zone temperature controllers so that the furnace can easily achieve the required temperatures in each heating zone.

8.1.2 Belt Speed

If the profile temperatures are acceptable, but the period it too long or short, vary the belt speed to achieve the required retention time. Increasing belt speed reduces process time, reducing belt speed increased time at temperature. Adjusting belt speed will also affect ramping time. Be careful to keep belt speed low enough to assure the product has adequate time to cool before it reached the exit belt roller.

8.1.3 Process Gas Inflow

Process gas introduced into the furnace through the chamber walls serves to keep the lamps ON and thereby improving process control. Too much gas will force lamps ON and use more power than may be necessary. Too little gas with allow the lamps to shut OFF. While the furnace is coasting, it is out of control and may result in uneven results.

The process gas flow can be adjusted to replenish the gas in each zone by multiples of the volume of that zone. Replenish rates for normal processing are 1-2x. If processing requires very low moisture and/or oxygen concentrations below 20 ppmv, higher replenish rates in the zones may be required to achieve good results. See section **8.5 Gas Flow** through **8.5.7 Process Gas Flow Guidelines** for detailed information of gas flow replenish rates and balancing the furnace.

8.1.4 Balancing the Gas Flow

One the process gas inflows are set, the exhaust stacks must be adjusted for the type of environment desired. If the process being run required very low moisture and/or oxygen concentrations, the furnace atmosphere should be positive (internal pressure higher than the pressure of the room). To establish a positive atmosphere in the furnace, sum the inflows, subtract excess gas amount (typically 400-1200 SCFH) and divide 15 to determine the stack exhaust flow settings.

If the process may give off volatile or poisonous gas, set the furnace to neutral or negative atmosphere (furnace internal pressure lower than room atmospheric pressure). To achieve a negative atmosphere, sum the inflows, add excess gas amount (typically 200-400 SCFH), and divide by 15 to determine the stack exhaust flow settings.

The furnace eductors are designed to extract the process gas from the furnace and cooling section internals at approximately 15 times the flow to the stack eductor. For example to extract 500 SCFH from the furnace via the stack, set the stack flow to 30-35 (500/15 = 33.33). See section **3.4**. See sections for 8.5 through 8.8 for process engineering considerations.

8.1.5 PID and Zone Power

While the furnace PID settings are preset at the factory, sometimes a process requires adjustment of these parameters to achieve desired results. In addition on computer controlled furnaces, adjusting the zone power settings can dampen furnace performance. Increasing zone power will increase furnace responsiveness.

In furnace with independent zone controllers, the Autotune feature can aid in optimizing zone controller performance. See section **8.4 PID Tuning** for more details.

8.2 Furnace Construction

The heating chamber technology allows for rapid heat-up and cool-down times. Stable temperatures of up to 960ºC can often be reached in less than 20 minutes. While temperature above 960ºC to 1000 ºC can be achieved, the furnace may have difficulty reaching stable operation near the furnace design temperature of 1000ºC. Radiant heating allows for rapid startups and profile changes and system stabilization.

The heating chambers consist of an outer metallic shell fabricated from either aluminum or stainless steel, lined with a refractory-ceramic-fiber (RCF) insulation. Controlled atmosphere heated sections allow process gas to pass through the RCF insulation.

8.2.1 Modules

The furnace is constructed from a number of basic modules which make up the furnace length.

For example, a RTC CU-915 is comprised of 6 modules

Module 1 – Loading Station

Module 2 – Entrance Baffle

Module 3 – 4-Zone Heating Chamber Module

Module 4 – Transition Tunnel

Module 5 – Controlled Atmosphere Cooling Module

Module 6 – Unloading Station

In some applications, longer cooling sections are required. Additional controlled atmosphere cooling modules, a water cooling system, or a forced air cooling module after the exit baffle may be added.

Another application may call for a longer heating section with an additional 4-Zone heating chamber module.

Every furnace heating chamber is constructed with 30-in. (76-cm) modules. Depending upon application requirements, the furnace can be configured for any size up to 16 zones. Each furnace is a custom arrangement from standard design modules, the layout and overall design is completed prior to the start of fabrication.

8.2.2 Throat

The throat of the furnace describes the maximum height of any product allowable through the process section. Depending upon configuration, throat clearance can range from 0.75 to 4 inches. The throat height has a significant impact on the thermal process profile as gas flow between chambers is significantly increased as the throat is increased.

Warning: Feeding items trough the furnace that exceed the throat clearance will damage furnace zone separators and may reduce furnace performance.

8.3 Heating Chamber Design

8.3.1 Zones

The heating chambers are divided into individually controlled **zones**. Each 30" chamber module can be divided into 1, 2, 3 or 4 zones. If the furnace requires more than 4 zones, additional heating chamber modules must be added. The zone configuration of your furnace depends on the type of processes your furnace will be running and is part of the project furnace design specification.

8.3.2 Infrared Heating Chamber

The chamber is insulated with a porous material and if the furnace is used in a controlled atmosphere application, pressurized process-gas entering **plenums** at the top and bottom diffuses through the porous insulation and enters the process area. The gas enters in high volume and with low velocity. As the gas diffuses, it becomes heated to the bulk temperature of the zone.

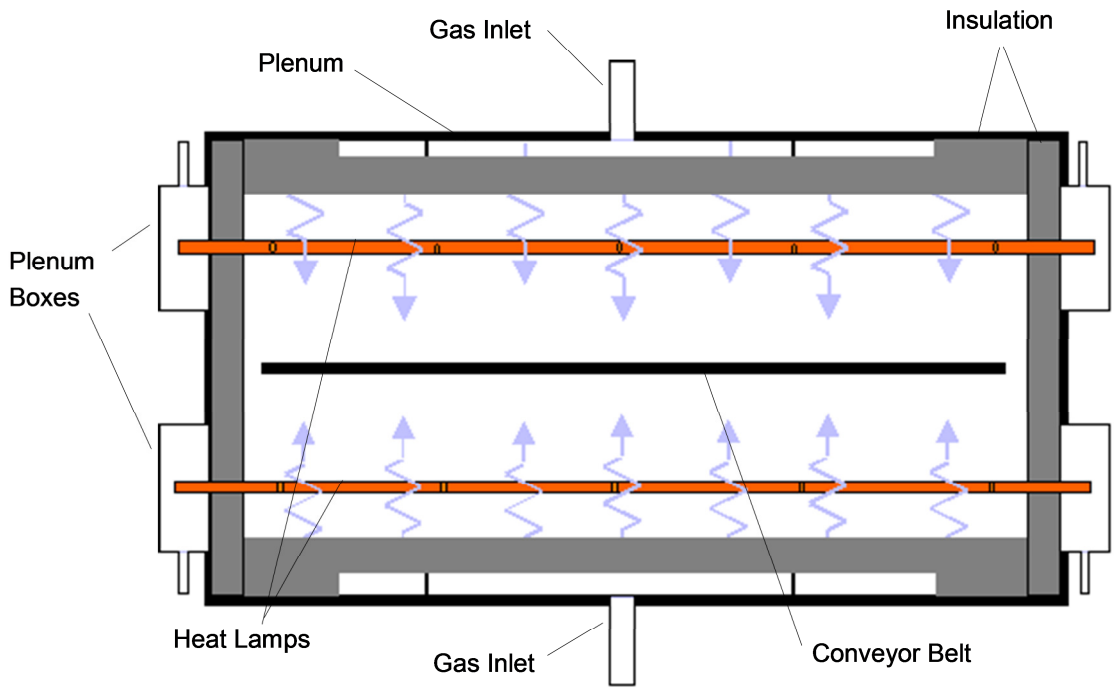


Figure 8-2 Heating Chamber Construction. End view

Plenum boxes may be specified and included as part of the hermetic seal option, which allows a light positive pressure to be applied to the ends of the heat lamps forming a highly controlled atmosphere condition.

Correctly balancing the airflow contributes greatly to the cleanliness of the chamber. When properly balanced, a high volume gas-flow is present from both top and bottom of the chamber. Effluents released from your product are swept along the centerline of the chamber to the exhaust ports, and do not rise to contact the upper surfaces or fall to contaminate lower surfaces.

Incoming process gas introduced through a large displacement area provides rapid purge times and low contamination levels. Typically, a process environment atmosphere of less than 10 parts Oxygen in 1,000,000 parts Nitrogen (<10ppm O2) can be achieved within about 10 minutes. Rapid purge times also allow for quick process environment replenishments as well as fast cool-down times.

8.3.3 Energy Type for Applications

Types of Energy. The ability to turn banks of lamps off and on via the zone lamps TOP and BOTTOM switches on the TEMPERATURE panel allows the user great flexibility in applying energy to each zone. Use just the top lamps in each zone for drying moisture or volatile organic compounds from the top surface of substrates or trays, or curing thermosetting compounds or coatings on wafers or polycarbonate materials. Use both top and bottom lamps in traditional furnace applications. Use just the bottom lamps to emphasize conduction heating of parts from the transport belt and from IR radiation on the bottom of metallic or ceramic parts carriers.

8.3.4 Placement

Lamp configuration within each zone is determined to achieve optimal power consumption based on the type of processes specified by the owner operator. Heat lamps can be packed closely together where high temperatures need to be reached quickly. For Holding Zones where rapid rises to high temperatures are not required, lamps are usually spaced further apart.

8.3.5 Wiring

Heating lamps are wired differently for each furnace. The actual amount of power available to each lamp is based upon the heat lamp wiring configuration and the AC input voltage. Lamps may be wired in parallel providing the highest available power to the individual lamp or in series, splitting the power with other lamps. Most systems are wired in a series-parallel configuration to optimize the use of available voltage and minimize current flow. Refer to the wiring diagram in the Operating Manual for heat lamp wiring details for a specific furnace.

8.4 PID Tuning Concepts

When the furnace is in operation, the power supplied to the lamps is under constant control. A special performance control is used to maintain consistent zone temperatures by adjusting the current allowed to reach the heat lamps. The control is referred to as a PID control loop. The name PID stands for **P**roportional + **I**ntegral + **D**erivative and represents the three terms used in the control loop.

When PID tuning, any changes that are made are sent directly to the controller modifying the way the controller responds to deviations from setpoint. Tuning the furnace allows the engineer to precisely control the temperature profile inside the furnace.

A complete understanding of how a PID loop works and how to tune it will greatly benefit the owner operator and product results.

In general, the PID equation takes on the following form:

$$\mathrm{CO} = G \cdot \left\{ (S - T) + \frac{1}{I} \int_0^{1\,\mathrm{sec}} T \cdot dt + D \cdot \frac{dT}{dt} \right\}$$

Where:

$T = \text{Temperature}$

$t = \text{Time}$

$G = \text{Gain Term Value}$

$S = \text{Setpoint Temperature}$

$I = \text{Integral Term Value}$

$D = \text{Derivative Term Value}$

The output from the three terms, the proportional, the integral and the derivative terms are summed to calculate the output of the PID controller. The following paragraphs review and explain the three components of the PID equation.

8.4.1 Gain

The proportional band is adjusted according to the following equation

PB °C = 100 °C / Gain

The higher the gain, the narrower the proportional band; the lower the gain, the wider the proportional band.

The gain value multiplies the difference between the setpoint and actual temperature. The difference between these two values is referred to as the **error.** (This does not mean that anything is wrong). The error is measured continuously, about once a second. When this difference is large, power to the heat lamps will be increased, or decreased, accordingly. When the error is small, power to the heat lamps will be maintained at present levels. Gain values greater than 1 amplify the controller's response to error (differences between temperature and setpoint).

Setting the gain too high will result in temperature over and under shoots. It is possible that the temperature will never reach a stable state. The temperature might oscillate around the setpoint.

Setting the gain too low will result in a slow response to temperature changes. The furnace will take longer to reach operating temperatures and will be slower to recover from temperature drops as the product soaks up heat.

Note: Since the gain value is a multiplier, it should not be set to zero.

Default values for gain vary for each zone and temperature setpoint range. Gain is typically set at default values from **50** to **125** for most applications.

8.4.2 Integral

With only gain operating, and no value set for integral and derivative, the controller acts somewhat like a thermostat. When the difference between temperature and setpoint (error) is zero, power to the heat lamps is maintained at current levels. When the temperature drops below the setpoint, power is increased until the temperature returns to the setpoint. This PID setting results in an operating condition where the measured temperature is often inappropriately far from the temperature setpoint.

The integral value is used to rapidly converge on the set point.

The **integral value** refers to the integer value entered in the recipe screen. The **integral term** is calculated automatically by the controller. The integral value multiplies the integral term.

The Integral term in the PID equation represents the average error (temperature difference) over a time interval of about one second and is updated continuously, accumulating error as a function of time.

The integral product (**integral value** multiplied by **integral term**) is added to the error. This integral product can make a significant difference to the PID control output signal especially if the current error is small.

Think of it this way: The difference between temperature and setpoint at any given time could be zero, but the average difference between temperature and setpoint over the length of time represented by the integral term is never likely to be zero. With an integral value of zero, power will be maintained at its current level even though the temperature is about to decrease. With an integral value greater than zero, multiplying the integral term, power will be increased slightly and the impending temperature drop will be not be as profound.

With a Gain and an Integral value entered in a recipe, the PID equation will always be adjusting the controller's output unless the both the **current difference** and **average difference** between temperature and setpoint is zero.

Larger integral values generate smaller responses from the controller. A value of 1, for instance, will use the entire average difference between temperature and setpoint for the correction value. A value of 2 will use half the average difference for the calculation. Entering very large integer values will have the same effect as entering zero.

Default values for integral vary for each zone and temperature setpoint range. Integral is typically set at default values from **6** to **12** for most applications.

8.4.3 Derivative

The derivative term of the PID equation is a value representing the rate of change of the temperature setpoint deviation. If, for example, the temperature deviation is accelerating away from the setpoint, the derivative term attempts to predict what the deviation will be some short time in the future. This behavior allows the derivative to sense a change in load early and attempt to counteract its effect ahead of time.

Suppose, for example, that the zone temperature is deviating downwards from the setpoint at 10°C/second. At the next measurement, the temperature is deviating downwards at a rate of 20°C/second. The derivative term will sense this acceleration away from the setpoint and counteract it by increasing the PID signal to the controller. The larger the derivative value entered in the recipe screen, the larger the correction.

A zero value may be appropriate for many processes with constant furnace loading (a continuous stream of similar parts entering the furnace).

For processes where furnace loading is uneven, such as when parts arrive from screen printers or non-buffered processes in an automated line, a non-zero derivative term may help the furnace respond more quickly when parts suddenly enter the heating zones.

Care must be taken when entering derivative terms higher than 4 due to the fast response of the IR furnace.

Detecting an accelerating deviation from setpoint requires at least three temperature measurements. Therefore, at least two seconds elapse before a correction can be made. Heat lamps are very responsive and very little amplification is needed to correct the lamp output. The derivative can show a downwards accelerating temperature deviation even though the temperature may have started increasing. This condition can result in an over correction.

Even when furnace loading is fairly constant, Derivative can vary for each zone and temperature setpoint range.

Default Derivative values are 1 to 3 for all applications.

8.5 Gas Flow

8.5.1 Gas Flow Basics

The most important factor in creating a safe and efficient process environment is gas-flow balance. The volume of process gas entering the system should be equal to the volume of exhaust gas leaving the system.

Gas flow entering the oven is controlled by **flow meters**. The flow meter arrangement is different for every furnace. A flow meter can be installed to supply gas for each individual zone or for various combinations of zones.

All furnaces are equipped with gas power exhausts. Compressed gas (usually air or nitrogen) is forced through a small hole in a small tube creating a venturi effect inside the exhaust stack. The forced high-speed gas flow drags the furnace atmosphere out with it. To regulate the rate of exhaust, each venturi is supplied by its own flow meter.

Correct gas flow through the venturi is a critical factor in achieving stable temperature profiles. For this reason, exhaust stacks cannot be connected to facilities ducting. Changes in facilities-ducting pressure would change exhaust pressure that would in turn change the gas flow within the furnace. The condition will lead to alterations in the thermal process profile.

Disruptions in gas flow in the process section can be caused by the following influencers:

- Close proximity of doors
- Close proximity fans
- Placing a furnace through a wall between rooms
- Attaching facility exhaust ducts directly to the furnace exhaust stack

8.5.2 Process Gas

Various forms of process gas can be utilized inside furnaces. Users may want to operate a pure N_2, O_2 or H_2 environment. Others will only need clean dry air (CDA). Whatever the case, the furnace can be factory configured in different ways to meet specific requirements. The following are some possible process gases.

A. Nitrogen

Many processes require the process environment be free, or almost free, of oxygen as the products would either burn or oxidize. Removing oxygen involves forcing the oxygen out by pumping in another gas. A relatively inert gas such as nitrogen is normally used for this purpose.

B. Forming Gas

Forming gas is the term used to describe any mixture of N_2 and H_2 gas. Without the Hydrogen option, only non-combustible gas can be used safely with the LA-306.

C. Hydrogen

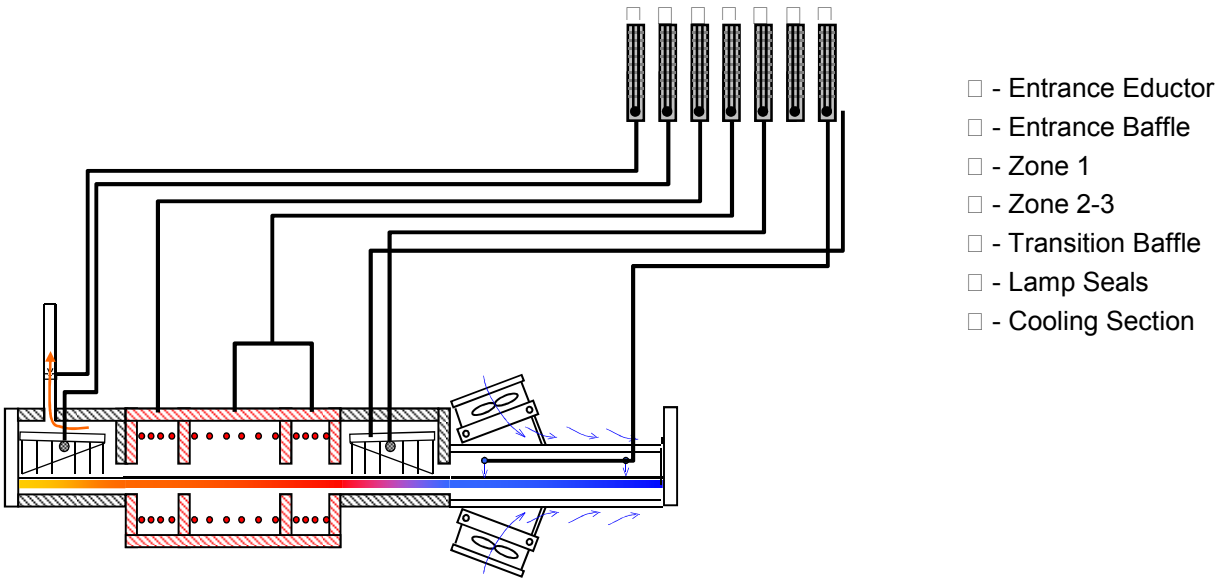
Other gases having a beneficial effect on a process can also be introduced into the process environment. Hydrogen, for example, is commonly used in reflow soldering processes to facilitate solder flow. Without the Hydrogen option, only non-combustible gas can be used safely with the RTC CU-915.

All processes with concentrations of H_2 higher than 4% mass percent require all H_2 automated safety features. When the concentration of H_2 gas required for the process falls below 4%, H_2 levels will not reach an explosive concentration inside a furnace.

8.5.3 Creating an Optimum Process Environment

To establish a process environment, the engineer will need to start with the number of times the air surrounding the product will need to be replenished. This figure depends very much on the process requirements and costs. Some processes give off large quantities of volatiles that will need to be removed, requiring higher gas flow rates than other, cleaner processes. The cost of the process gas will also need to be taken into account, as quick replenishment times will use significant volumes of gas. For new processes, it may be safest to start with a high gas flow rate that can be adjusted downwards until the test product stops coming out clean.

The first step in calculating the flow rates will be to calculate the internal volume of the furnace chamber and multiply the answer by the number of times per hour that the atmosphere needs replenishing. The result is the total gas flow per hour for the chamber.



8.5.4 Calculate the Internal Volume of an RTC CU-915 IR Furnace

Example 1:

The process engineer determines the thermal process ***replenish time*** *is 30 seconds.*

Given: *Replenishment Requirement: 30 seconds / replenish*

Belt Width: 15 in.

Process Section Dimensions (Not including Open Air cooling modules)

The better the estimate of internal volume, the less tuning required.

	L (in)	*W (in)*	*H (in)*	*V (ft^3)*
Entrance Baffle	*38*	*16*	*6*	*0.89*
Zone 1	*10*	*16*	*9*	*0.83*
Zone 2	*20*	*16*	*9*	*1.67*
Zone 3	*20*	*16*	*9*	*1.67*
Zone 4	*10*	*16*	*9*	*0.83*
Trans Tunnel	*10*	*16*	*6*	*0.56*
Cooling	*63*	*16*	*6*	*3.50*
Exit	*4*	*16*	*6*	*0.22*
Lamp Seals	*240*	*1*	*2*	*0.28*
Total Internal Volume				*10.2*

8.5.5 Calculate Replenish Rate

Example 1 (cont):

Convert to cfh:

Volume of furnace = 10.2 cf / replenish

1 minute = 60 seconds

60 seconds/min / (30 seconds / replenish) = 2.0 replenishes / min

(2.0 replenishes / min) x (10.2 cf / replenish) = 20.4 cfm

Balancing Gas Flow, Q = 1224 cfh (actual cubic feet per hour)

From these calculations you can balance the furnace environment with a total gas flow of 1224 cfh.

Note: although the above result is not true SCFH, it can be used to balance the furnace. The flowmeter scales are labeled in SCFH, but are not corrected for actual conditions. To calculate true SCFH, convert using Boyles law:

Correct for temperature and pressure to convert from cfh to standard cubic feet per hour (SCFH), assuming the inside of the furnace is at 1 atmosphere:

$$\text{scfm} = \text{acfm x } \frac{(\text{Std Temperature x Actual Pressure})}{(\text{Act Temperature x Std Pressure})}$$

Actual Furnace Temperature, T_1 = 38C + 273 = 311 K

Actual Pressure, P_1 = 0 kPa + 101.3 kPa = 101.3 kPa

Standard Temperature, T_s = 21C + 273 = 294 K

Standard Pressure, P_s = 101.3 kPa

$$\text{scfh} = 1224 \text{ x } \frac{(294 \text{ K x } 101.3 \text{ kPa})}{(311 \text{ K x } 101.3 \text{ kPa})}$$

True Standard Gas Flow, Q_s = 1157 scfh (21C, 101.3 kPa)

Standard cubic feet per hour can be used to determine plant compressed air requirements.

8.5.6 Balancing Gas Flow

Once the total gas flow has been determined for the process, the process engineer can then determine the balance of the gas flow.

Balanced gas flow means that the same volume of gas enters the chamber as exits.

❶ First to determine the quantity of gas that should be introduced to the each heating chamber: Divide the Balancing Gas Flow among each of the heating chamber zones and baffles for which the furnace has control.

❷ To determine the total gas flow to the eductors, first subtract the volume excess gas flow (flow to exit from entrance and exit openings) and then divide the result by 15. The approximate volume of air drawn out by the venturi created by the eductor is 15 times the flow rate.

❸ Divide the total eductor gas flow among the available eductors.

❹ The sum of the eductor gas flow and the Balancing Gas Flow is the gas consumed by the furnace.

Refer to Example 2 example shown on the following page.

Note: A balanced gas flow does not guarantee the best or most economical environment for your process. After following this procedure, gas flow may still need adjusting to achieve an optimum and safe environment.

A. Calculate the Balancing Flow

Example 2:

Given: *Desired Excess Gas Flow = 400 SCFH*

Balancing Gas Flow = 144 Lpm (from Example 1)

Gas Entering Zones

Entrance Baffle	*50*	*SCFH*	❶
Zones 1	*190*	*SCFH*	
Zones 2 - 4	*190*	*SCFH*	
Transition Top	*180*	*SCFH*	
Transition Bottom	*90*	*SCFH*	
Lamp Seals	*80*	*SCFH*	
Cooling	*225*	*SCFH*	
Balancing Gas Flow in =	*1005*	*SCFH*	
- Excess Gas Flow =	*400*	*SCFH*	❷
Evacuation Gas Flow =	*605*	*SCFH*	
Eductor Flow Divider ÷	*15*		
Total Eductor Gas Flow =	*40*	*Lpm*	
Entrance Stack Eductor	*20*	*Lpm*	❸
Trans Stack Eductor	*20*	*Lpm*	
Total Eductor Gas Flow =	*40*	*Lpm*	

Gas Consumption

Total Gas Flow in	*1005*	*SCFH*	
Eductor Gas Flow	*40*	*SCFH*	
Total Gas Consumption =	*1040*	*SCFH*	❹

This method provides a good starting point for balancing the gas flow in your furnace. It is, however, an approximate method so additional tuning will be required.

8.5.7 Process Gas Flow Guidelines

The following are guidelines for some common processes performed in furnaces.

1. If faster cooling is required – increase flow to the entrance eductor while reducing flow to the transition or exit eductor. This will prevent hot air from the heating chamber from carrying over into the cooling section.

2. For equilibrium profiles – set the flow to the zones at about the same rate. This will assist in keeping a steady flow of process gas around the product during heating.

3. For peaked or non-equilibrium profiles (i.e. solder reflow or solar cell firing) – increase flow to the middle zones and reduce flow at the beginning and ending zones, also increase flow to cooling sections. This will help the product achieve high temperature under IR radiation and allow for quick cooling.

4. In a long steady peak profile – increase flow to exit or transition eductor while reducing flow to the entrance eductor. This will draw the air to the end of the heating chamber using convection heating to assist in raising the product to its final temperature.