DESIGN OF A HIGH TEMPERATURE PROCESS CHAMBER for the SELECTIVE LASER SINTERING PROCESS

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ABSTRACT

The quality of parts made by the Selective Laser Sintering (SLS) process depends directly on controlling heat transfer to the part-bed. In this paper, we detail the thermal design of a HIGH TEMPERATURE PROCESS CHAMBER to be used for building parts from metals and ceramics. Modeling and experimental techniques are used to design radiant and convective heat transfer schemes to apply uniform heat flux to the part-bed. At the completion of the project, we expect to have a test-bed to study the effects of radiant and convective heat transfer on part quality in a high temperature environment.

BACKGROUND

Background of the HTW Project

In 1989, work began on a new SLS machine to directly sinter parts from metals and ceramics. This High Temperature Workstation (HTW) would require the powdered material to be heated to sintering temperatures in excess of 1500°C. One way to obtain these temperatures is to use a high-power laser. The decision was made to obtain a 1.1kW CO_2 laser and to design a workstation around this high-power laser. [Das]

In polymer systems, experience has shown that applying laser energy to a cold powder-bed often causes the newly formed layer to deform so that it curls up out of the plane of the part-bed. This phenomenon is known as "curling". The use of a heater to pre-heat the part-bed has been found to control the curling problem in polymer systems.

The first High Temperature Workstation was brought on line in October of 1991. This workstation utilized the 1.1 kW CO_2 laser, but had no heating system to pre-heat the powder. Single layer experiments were done using stainless steel and copper powders. Multiple layer experiments were then conducted using two alloy systems. [Wu]

As suspected, curling was a problem. Since this chamber had no built in heating, there was no way to control thermal stresses. A hot-plate heater was used at the base of the powder, which produced some improvement in part quality under certain conditions. This heating method, however, is impractical for multiple layer parts.

The Next Stage: High Temperature Selective Laser Sintering

This paper details the design, development, and testing of a HIGH TEMPERATURE PROCESS CHAMBER, the key component of the new HTW presently under construction. This phase of the HTW project required an evaluation of process requirements, the selection of a Heating Method and Temperature Control System, and the design, construction, and testing of a HIGH TEMPERATURE PROCESS CHAMBER. First, Design Specifications for the HIGH TEMPERATURE PROCESS CHAMBER were developed. Then, conceptual designs for a Heating Method were developed. The final conceptual design was evaluated and optimized using heat transfer models. The PROCESS CHAMBER was designed and built to accommodate the heating method. Finally, the completed chamber was performance-tested to identify any potential problems, and to compare real performance to model predictions.

DESIGN SPECIFICATIONS

A Design Group was formed to develop Design Specifications for the HIGH TEMPERATURE PROCESS CHAMBER. Researchers in the Material Science area formed an important part of the design group, since they would be the end users of the HTW. The group developed three important Design Specifications.

Maximum Temperature Specification

After examining some of the properties of the materials to be used in the HTW, the Design Group set a goal for a Maximum Operating Temperature of 1300°C. This value represents the final steady-state temperature that the powder-bed should reach with the heating system operating at full capacity. The group then set a Normal Operating Temperature range of 100°C to 1000°C. We define Normal Operating Temperatures as those temperatures which fall within the controllable range of the heating system.

Temperature Uniformity Specification

A high degree of Temperature Uniformity is required to eliminate curling. The Temperature Uniformity Specification was therefore one of the most important design considerations, but also one of the most difficult to quantify. Since surface temperature uniformity depends on many factors and is material dependent, the group decided to evaluate the potential uniformity of each heating method based on its heat flux uniformity. Since there is no direct relationship between heat flux and temperature distribution, no value was set for this requirement. Rather, the Design Group made the decision to simulate the heat flux distribution for different heater designs, and to use the results as an important selection criterion when choosing between different heating methods.

Controllability Specification

The controllability of the heating system depends on the dynamic properties of both the heating system and the control system. At this point in the design process, the design group could not quantify the Controllability Specification, but decided that it should be an important criteria in selecting a heating method.

Heaters vary greatly in thermal mass. In low thermal mass systems, the power output can be changed rapidly. In high thermal mass systems, power output changes very slowly in response to power input. A heating system with a low thermal mass is most desirable for flexibility in process control.

HEATING METHOD SELECTION AND ANALYSIS

In addition to the Design Specifictions given above, several other design constraints made selection of a heating method quite difficult. For example, the heating method had to allow the laser to scan the entire area of the part-bed. Simple models had shown that a very high heat flux is required to meet the Maximum Temperature Specification. In the selection process, the design group examined many high-power heating methods, including quartz infrared heaters, graphite ring heaters, direct resistance heating and induction heating.

Selection and Application of Dual Infrared Panel Heaters

The design group selected a dual infrared panel heater arrangement as the heating method for the HTW (Fig. 1). A similar system was developed by Brubaker for an infrared drying oven. High-density quartz panel heaters were selected. The system has a total power output of around 20 kW.

The design group chose the dual panel heater arrangement as the most promising design for several reasons. Most importantly, quartz heaters can deliver a higher surface heat flux than any other of the heating methods investigated (up to 780 Watts per square centimeter at the heater surface). Also, Brubaker's work suggested that the orientation of the heaters could be optimized to obtain a uniform heat flux. Finally, these heaters have a very low thermal mass which gives them excellent controllability. Their low thermal mass allows them to reach full power output in about one second.

Thermal Modeling and Analysis

Now that commercially available heaters had been found, the feasibility of the heating method could be evaluated. After we determined that the heaters could provide enough heat flux, two issues remained to be investigated. First, the heaters needed to be oriented to produce a relatively even heat flux across the part-bed. If it was possible to obtain an even flux, then an orientation had to be chosen to obtain the best combination of heat flux uniformity and heater efficiency. The following model was used to help achieve both of these goals.

For radiant heat transfer between two surfaces A and B in space, the heat flux from surface A to surface B is directly proportional to $F_{a\text{-}b}$, the view factor from A to B. This implies that if the view factors could be calculated, then the heat flux uniformity between the two surfaces could be evaluated. In our case, surface A is the heater and surface B is the powder-bed.

A simulation program was developed that calculates the view factors from two planes, representing the radiant heaters, to an array of differential planar elements, representing the powder-bed (Fig. 1). The two heaters are angled into the plane of the powder-bed at an angle ϑ. The outside edge of the two heater planes is at a height **h** above the powder-bed. The heaters are separated by a distance **d**. The program plots the view factor distribution across the plane of differential elements representing the powder-bed. The plane is the same size as the projected area of heaters. An efficiency is calculated as the percentage of infrared radiation that strikes this plane.

After evaluating several different heater orientations, the model predicted that a very uniform heat flux could be obtained for certain orientations. Figure 2 shows the view-factor profile for the final chamber design. At the center of the bed, the view factor is approximately 0.40. For this configuration, the model predicts that approximately 17% of the energy from the heaters should directly reach the powder-bed.

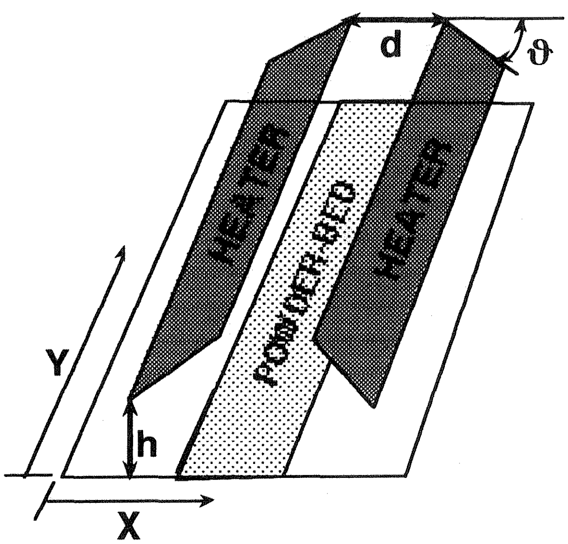

Figure 1: Heater Configuration

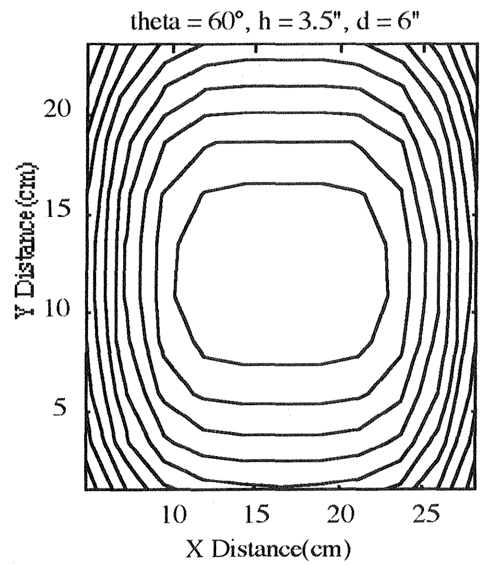

Figure 2: View Factor Contour Plot

SYSTEM DESIGN

Three principle systems make up the overall design of the HIGH TEMPERATURE PROCESS CHAMBER. The Chamber itself provides a sealed sintering environment. The Laser Window Cylinder isolates the laser window from the chamber environment. A Gas Handling System provides process gas to the Chamber without disturbing the temperature distribution on the part-bed. Finally, the Temperature Measurement and Control System measures the surface temperature of the part-bed and adjusts heater power to maintain a user-set temperature.

Chamber Construction

Design Considerations

The chamber must provide a controlled sintering environment. It must be gas tight, yet allow energy form the laser and from the heaters to reach the powder-bed. It must contain and provide access to the powder-bed and accommodate leveling and powder-feed systems.

Design Solution

The chamber, shown in Figure 3, is constructed of 3/4" thick carbon steel plate. The heaters are mounted outside of the chamber. Quartz windows mounted in the chamber walls allow the infrared energy from the heaters to reach the powder-bed. To access the interior of the chamber, the chamber bottom plate detaches, eliminating the need for an access door. Viton™ 0-rings seal all non-permanent joints. The entire interior of the chamber is lined with ceramic-fiber insulation to minimize heat absorption by the chamber walls.

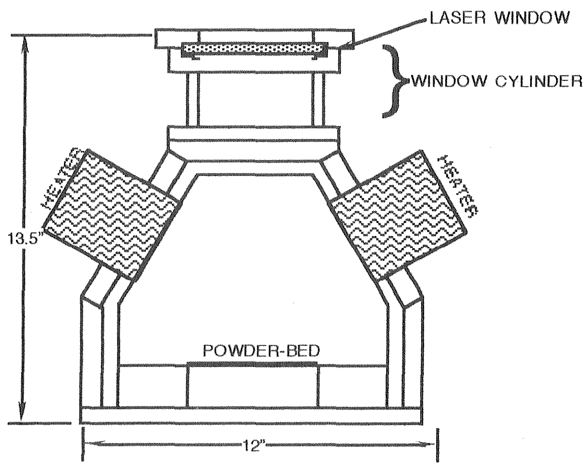

Figure 3: Chamber Configuration

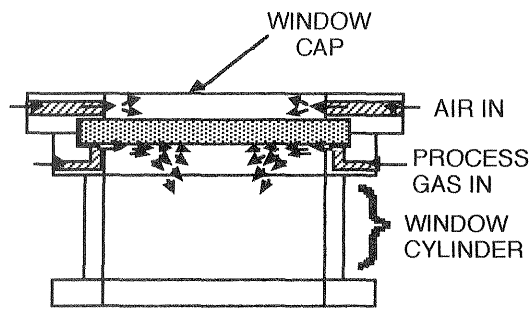

Figure 4: Window Flow Scheme

Laser Window Cylinder

Design considerations

The most important function of the Laser Window Cylinder is to keep the laser window below its high-temperature limit. Heat transfer analysis has shown that the window would experience a high heat flux from the chamber, and needs to be cooled.

In the previous HTW, the laser window tended to accumulate deposits from inside the chamber. Gas-born powder particles and vapors were carried up to the window by free convection from the hot powder-bed. In the past, a gas jet located in the wall of the Window Cylinder was used to purge the window. This method had some success, but produced turbulence that allowed deposits to accumulate on the edges of the window. In the new Window Cylinder, we hoped to achieve a significant improvement in this area.

Design Solution

An aluminum cylinder and cap were constructed to hold the laser window (Fig. 4). The window holder has provisions for gas flow across both sides of the window. The inside surface of the window cylinder has a gap that allows process gas to flow across the entire exposed surface of the window.

The cap also has provisions for gas flow, in this case across the outer surface of the window. Clean air is directed at the window through two jets, located at opposite ends of the cap.

Gas Handling System

Gas flow through the chamber and across the part bed will affect temperature distribution and part quality. An experimental approach was used to help design the Gas Flow System for the HIGH TEMPERATURE PROCESS CHAMBER.

Design considerations

We performed experiments with a thermal imager to determine the effect of convective flow on temperature uniformity across the powder-bed. The imaging experiments showed that free convection provided the most uniform temperature distribution across the powder-bed. The procedure and more complete results are given in the System Performance section.

Keeping in mind that gas flow must be introduced into the window cylinder to keep the window cool and clean, we used the experimental methods detailed below to help develop a gas flow system. The primary design consideration was to ensure that any gas flow scheme left the gas above the part-bed undisturbed so that it experienced only free convection. In the design of the Gas Flow System, another important consideration was to obtain efficient purging of oxygen and sintering by-products from the chamber.

Experimental Flow Analysis

In order to visualize the flow patterns established inside the HIGH TEMPERATURE PROCESS CHAMBER, a mock-up of the chamber was constructed. This test chamber was a 1:1 scale model of the actual chamber, but was constructed of clear polycarbonate sheet. The mock-up consisted of a window cylinder and the main chamber. In the actual chamber, the part bed would lie directly below the laser window cylinder in the plane of the plenum, which is an inch and a half above the base of the chamber. For a tracer, dry ice and water were placed in a cylinder located where the part bed would be. The boiling of the dry ice created CO_2 vapor. This vapor allowed us to observe the flow patterns over the part bed.

At this point, the greatest concern was to determine how flow from the window cylinder would effect the bed. We developed and tested a simple flow scheme (Fig. 5). In this scheme, all of the gas flow into the chamber entered through the window cylinder. The gas was drawn around the part-bed through holes in each plenum, which were located in a symmetrical pattern to either side of the part cylinder. The gas then exited the chamber through an exhaust port in the feed-side end of the chamber.

Design Solution

We found that for gas flow rates of less than 40 liters per minute, a stable flow pattern could be achieved around the part bed with the simple flow scheme described above. At these flow rates, we observed that the flow patterns of the CO_2 vapor over the part-bed remained undisturbed. From this observation, we concluded that the gas around the part bed also remained undisturbed, which was the primary design goal for the Flow System.

In the HIGH TEMPERATURE PROCESS CHAMBER, we plan to install two cross flow heat exchangers, one on each side of the part-bed. In the final system, gas will enter the chamber through the Window Cylinder, pass through the fins of the heat exchangers, and travel beneath the plenum to the feed-side of the chamber, where it will exit through an exhaust port. The purpose of the heat exchangers is to absorb the excess heat from the chamber and to cool the gas before it is released to the building exhaust system.

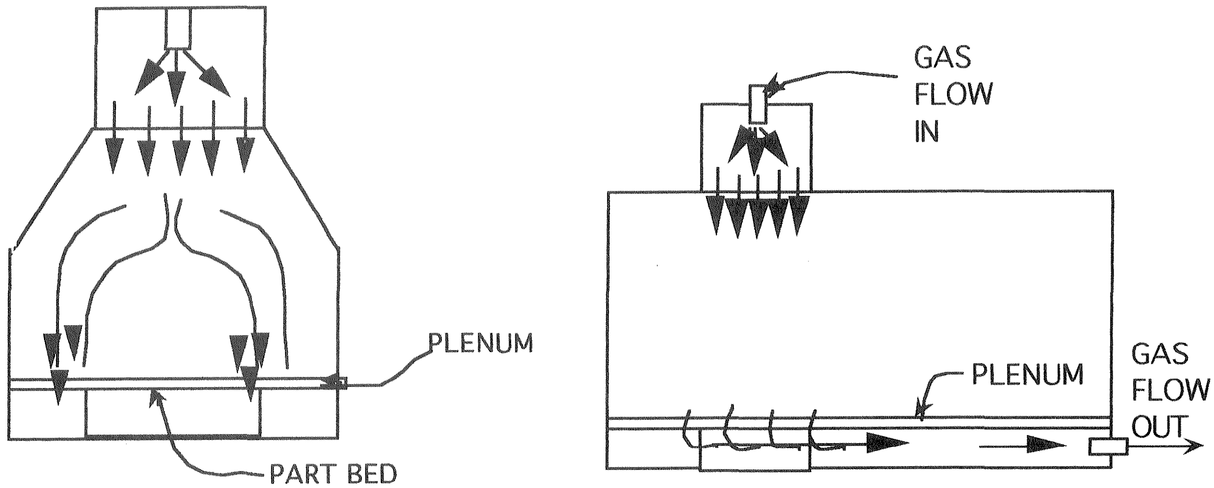

Figure 5: Chamber Flow Scheme

Temperature Measurement and Control System

The function of the temperature measurement and control system is to maintain the surface temperature of the powder-bed at a user specified set-point. In order to provide this function, three major sub-systems are required to: measure the surface temperature of the powder-bed; monitor the surface temperature and produce an output control signal; and supply power to the heaters in response to the control signal.

Design considerations

Measuring the surface temperature of the powder-bed presents some unique challenges. Measurements must be unaffected by radiant flux from the heaters. Measuring instruments must not interfere with the powder leveling roller, which passes over the entire surface of the powder-bed during each leveling operation. For these reasons, a non-contact method of temperature measurement was chosen.

Non-contact temperature measurement is generally done with an infrared (IR) thermometer. In selecting an IR thermometer, temperature range is an important consideration. For our process, we desired an instrument that could measure temperatures from room temperature to about 1500°C. Other important parameters include spectral response and field-of-view.

To automatically maintain the set-point bed temperature, a Process Controller is required to read and display the input signal from the temperature sensor and output a control signal to the heater Power Control system. In selecting a Process Controller, several design parameters must be considered. These include the desired control scheme, input signal compatibility, and output signal compatibility.

Design Solution

A Raytek IR thermometer was chosen to measure the surface temperature of the powder-bed. The instrument has a measurement range of 260°C to 1700°C. Its spectral response is 3-5μm, which makes it insensitive to reflected energy from the heaters. The IR thermometer has a field of view that produces a spot size of approximately one inch on the powder-bed. It was mounted outside of the chamber, and sees its target through a sapphire window mounted on top of the chamber.

An Omega PID process controller was chosen to control powder-bed temperature. The controller accepts a 4-20 mA input signal from the IR thermometer and sends a 4-20 mA control signal to the Power Controller.

A phase-angle-fired SCR power controller was selected as the power supply for the heaters. This 208V single-phase power supply supplies power to the heaters in response to the control signal from the Process Controller. A manual control mode is also available.

SYSTEM PERFORMANCE

When the chamber was completed, we developed a test plan to evaluate the performance of the chamber before it was installed in the workstation. Performance objectives were first developed, and then a series of tests were designed to evaluate the performance of the HIGH TEMPERATURE PROCESS CHAMBER.

Extended Burn-in Test

The main purpose of the Extended Burn-in Test was to determine if the heater windows and seals could withstand the temperatures to which they would be subjected. Another purpose of the test was to examine the affect of insulation on chamber and seal temperatures.

In this simple test, both ends of the chamber were removed, and a table-fan was used to blow air through the chamber for convective cooling. The heaters were run for 30 minutes, and then the condition of the window seals was inspected.

The first time this test was run, the Viton™ o-ring seals started to burn after about 10 minutes of heater operation at full power. The second time the test was run, the ceramic fiber insulation was installed inside the chamber. This time, the seals remained intact, and the chamber walls remained much cooler. This indicates that the seals absorbed most of the heat from the chamber walls, not directly from the heaters.

Water Bath Tests

The main purpose of the Water-bath Tests was to determine the efficiency of the heating system. In this case, we have defined efficiency as the proportion of the energy supplied to the heaters that reaches the heated surfaces.

Two tests were performed. The objective of the first test was to determine the heat flux across the entire area of the part-side of the chamber module base. In the second test, the objective was to determine the heat flux across the part-side of the powder-bed only. For each test, a tray containing a known weight of water was placed in the chamber, the heaters were turned on for 30 seconds, and the change in temperature was measured.

In the first water-bath test, the chamber base received an average of 134 kJ of energy. When averaged over the 30 seconds of the test, this works out to an average power 4.47 kW. The heat flux per unit area was 41 W/in^2 or 6.4 W/cm^2. The electric power input to the heater was maintained at 16.6kW. This yields an efficiency of 27%, which means that 27% of the electrical energy input to the heaters was converted into heat on the part-side of the chamber base.

The results of the second test indicate that the powder-bed will receive an average heat flux of 8.58 W/cm^2 , yielding an efficiency of 18% on the powder-bed.

IR Scanner Tests

One of the most important design criteria for the heating system was to produce very uniform bed temperatures. In measuring the temperature distribution, we hoped to accomplish two goals. First, we wanted to see if the measured distribution coincided with what we expected from the View Factor Optimization. The second goal was to see how different parameters affected temperature uniformity. Tests were performed to determine how temperature distribution was affected by gas flow across the powder-bed and by chamber wall reflectivity.

To perform the IR scanner tests, the IR scanner was placed on top of the chamber, where it looked down the hole where the window cylinder would normally be installed. During each test, the heater power was kept constant by maintaining heater power at 30 A. A 3-5 μm filter was used to minimize the effect of reflected IR energy on the temperature reading. In each test, the specimen and chamber were set up and the heater power was turned on. After the temperature profile reached steady-state, the output from the IR scanner was recorded on video tape.

In one of the most important tests, the effect of convection across the powder-bed was investigated. In this test, the flow velocity across the powder-bed was varied using a table fan. The results showed that natural convection produced the most uniform temperature distribution. These results helped motivate the gas flow scheme described previously. The other significant result of the IR Scanner tests showed that applying a reflective foil to the inside surfaces of the chamber increased the bed temperature significantly.

PROJECT STATUS AND FUTURE DEVELOPMENT

At this time, the performance of the HIGH TEMPERATURE PROCESS CHAMBER has been tested, and the results have been quite encouraging. Temperature distributions have been quite good, and bed temperatures in excess of 600°C have been obtained in brief tests. The only problem has been with cooling the laser window. This problem is detailed below. All systems are operational as described except for the Gas Flow System and the Temperature Control System. Other significant long and short term goals are given below.

Laser Window

In preliminary testing, the anti-reflective coating on the zinc-selenide laser window was damaged from excessive temperatures. The problem appears to be that the coating absorbed more energy than we predicted. Further heat transfer analysis is being conducted, and trials are being conducted with a sodium-chloride window, which can tolerate much higher heat fluxes.

Radiation Absorbers

The HIGH TEMPERATURE PROCESS CHAMBER has been shown to effectively heat the powder-bed, although only 18% of the radiant energy directly strikes the bed. The rest of this energy heats the process gas and the chamber itself. This excess heat must be removed if the HTW is to operate for long periods of time. A method to remove this extra heat has been studied and is being implemented on the HTW. Two water-cooled radiative absorbers are to be mounted on either side of the part-bed. Analysis predicts that the absorbers will remove about two-thirds of the excess heat.

Feed-Side Heating

The present heating system heats only the part-side of the powder-bed. Past experience has shown that leveling "cold" powder from the feed side on a hot part-bed caused curling problems. To combat these problems, a small (~2000W) feed side heater will be installed in the chamber.

Phase III: The Next High Temperature Workstation

The next long-term goal for the High Temperature Workstation project is to make a process chamber that has high vacuum capability, in addition to high-temperature capability. This next phase in the HTW project will not be initiated until significant test data from this system is collected and evaluated.

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