Design of Humidifying System for the Powder Bed of the Three-Dimensional Printing Machine

by

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

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Abstract

Three-dimensional printing enables the production of parts directly from a computer drawing by selectively applying binder to a layer of powder and stacking the layers up. The surface roughness of this parts is greatly dependent on the binder's ballistic impact on the powder. Dry powder tends to scatter when hit by the binder droplets, creating very uneven surfaces. Moist powder remains close packed, and the surface roughness improves. A humidifying system for the powder bed of the prototype three-dimensional printing machine was designed. It consists of an ultrasonic humidifier and an aluminum vent that redirects the moisture flow from the humidifier. The moisture flow has to cover the whole powder bed uniformly, to keep the powder moist while the machine was printing. A recollection system at the other side of the powder bed redirects the moisture flow out of the 3DP machine.

Thesis Supervisor: Emanuel Sachs
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Chapter 1

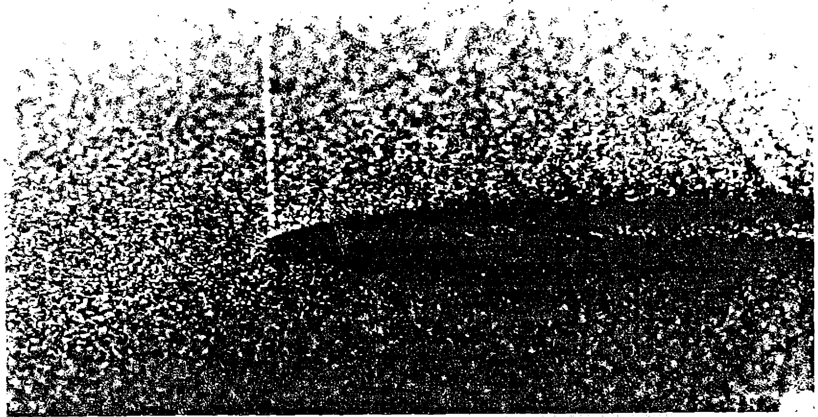
Introduction

Three dimensional printing is a process by which a computer drawing of a three-dimensional object (done in CAD or some other drawing software package) is transformed into a real object at the push of a button. The three-dimensional printing (3DP) machine does this by selectively applying binder material to a layer of silica powder, and stacking these layers up until the object is completed. The powder not held by the binder is shaken loose, and the object can be taken out.

The advantages of a machine like this are numerous, including the capacity to create complex geometries for metal casting molds, in relatively short time, and with great accuracy. A problem that arises is ballistic impact damage. The binder material is released above the powder at certain distance and with great velocity. Dry powder tends to scatter when hit by the binder, leaving non-uniform powder amounts along the layers and edges of the object. When the object is finished, this unevenness of powder densities translates into very rough surfaces, unacceptable for certain applications (such as turbine blades). If the powder were treated with a fixative or moisture, then there would be minimal scattering due to ballistic impact from the binder, and surface roughness would improve a lot (see Figure 1-1).

The purpose of this thesis was to design an effective way of applying moisture to the silica powder while the 3DP machine is working (and binder is being applied). In the next chapters, the analysis of the problem for the prototype 3DP machine will be presented, with the corresponding experiments. The final solution with a detailed

Ballistic Impact



When the binder hits loose powder, it
can cause some balistic damage.

If the powder is treated with a fixative or with moisture,
the ballistic damage can be reduced or eliminated.

Figure 1-1: Ballistic Impact Damage

design will follow, and the last chapter will deal with the conclusion, along with the last issues that remain to be solved, and/or looked at.

Chapter 2

Analysis of the Problem

The basic problem of this project was to deliver moisture to the powder layers on the 3DP machine without it interfering with the normal operation of the machine. In the 3DP prototype, this meant delivering a uniform flow of vapor over a powder bed roughly six inches wide by twelve inches long. The source of the moisture flow had to be out of the way from all the moving components of the machine, namely the binder printhead, the cross-bar roller mechanism, and the powder bed itself. There was also concern about the moisture flow past the powder bed, and if it would damage the electrical and mechanical components of the machine, so there was a need for a collection system as well. Again, this collections system could not interfere with the moving parts of the machine. Basically, we needed a moisture flow source and a moisture recollection system.

2.1 Moisture Flow Source

The obvious solution for the moisture source was to use a humidifier, and redirect its flow to go across the powder bed. Two types of humidifiers were tested:

Bionaire "Clean Mist" Humidifier this unit was basically a vaporizer. It used film boiling to produce the mist.

HolmesAir "Cool Mist" Ultrasonic Humidifier this unit did not rely on boiling, but rather it created a fine mist with ultrasonic vibrations of a transducer.

For each humidifier, different vents that redirected the flow of the mist were tested. Figure 2-1 shows the shapes of these vents. The vents were:

1. **simple hose**- this was the previous solution before the problem was looked at more seriously

2. **manifold**- two pieces of tubing, perpendicular to each other. The cross-tube has individual holes, spaced evenly across it, and the vapor comes out through them

3. **individual hoses**- each hose was attached to the humidifier and placed on an array at even spaces along the powder bed side

4. **Nozzle (back-to-front)**- this nozzle had a hose-sized entrance hole, and it narrowed down to a long, narrow exit, that was as long as the powder bed long side

5. **Nozzle (side-to-front)**- this nozzle had the hose coming in from the side, and was triangular in its side cross-sectional shape, with a long and narrow exit

6. **Nozzle-vent**- this was the only attachment that didn't use a hose as the first connection to the humidifier.

The tests consisted mostly of visual observation of the behavior of the moisture flow over a mock-up powder bed made out of wood and chipboard, seven inches by thirteen inches. The vents were positioned over the mock-up powder bed at approximately 1 5/8 inches, and away from it 1 1/4 inches to simulate the geometric constraints of the prototype machine. The ideal result would be a uniform, laminar flow of mist, about an inch thick above the powder, that covered the whole powder bed area continuously while the humidifier was on (see Figure 2-2)

Early on the project, it was decided that placing the vent along the long side of the powder bed was more efficient, since that way the vapor had less distance to

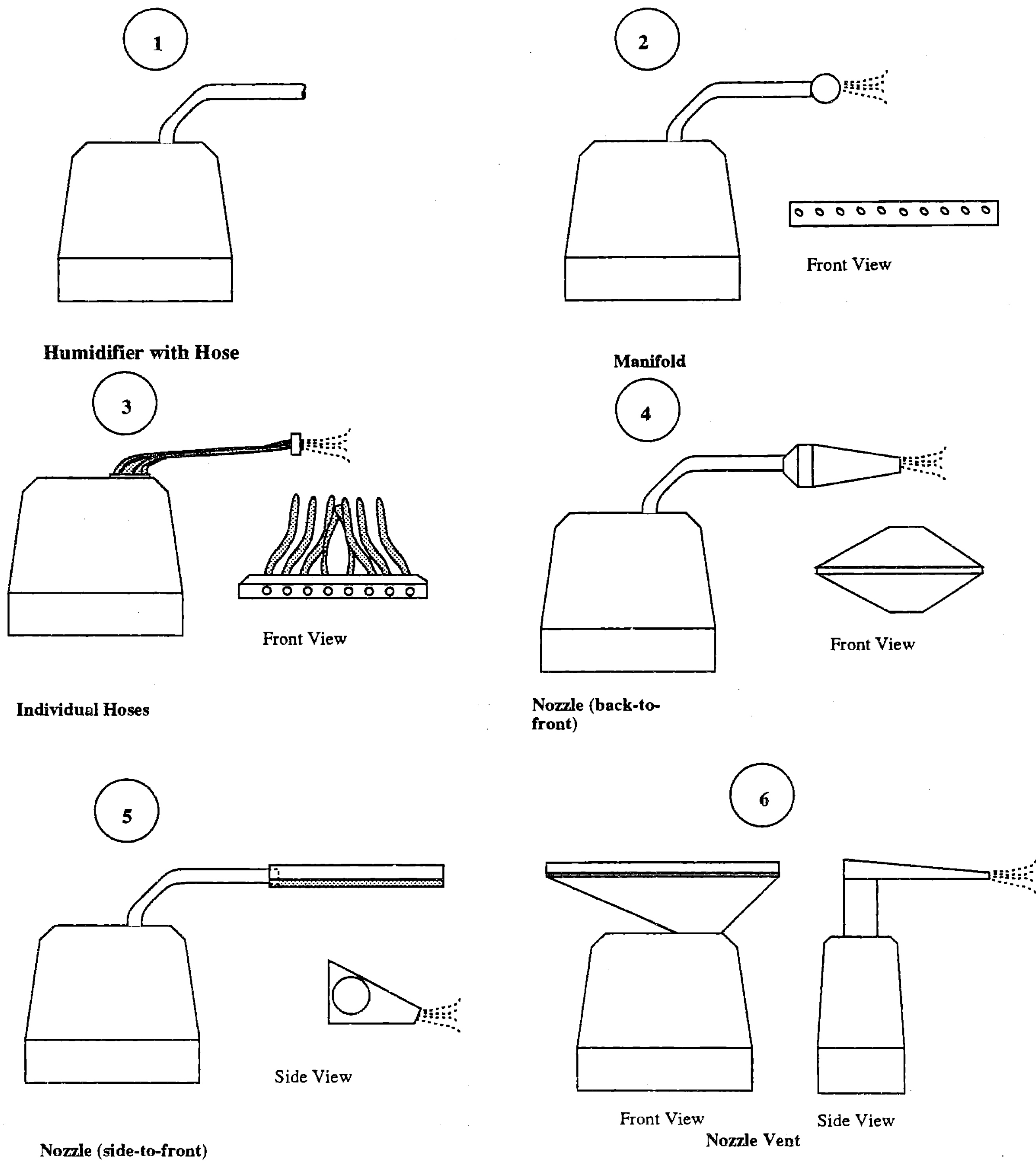


Figure 2-1: Types of Vents Tested

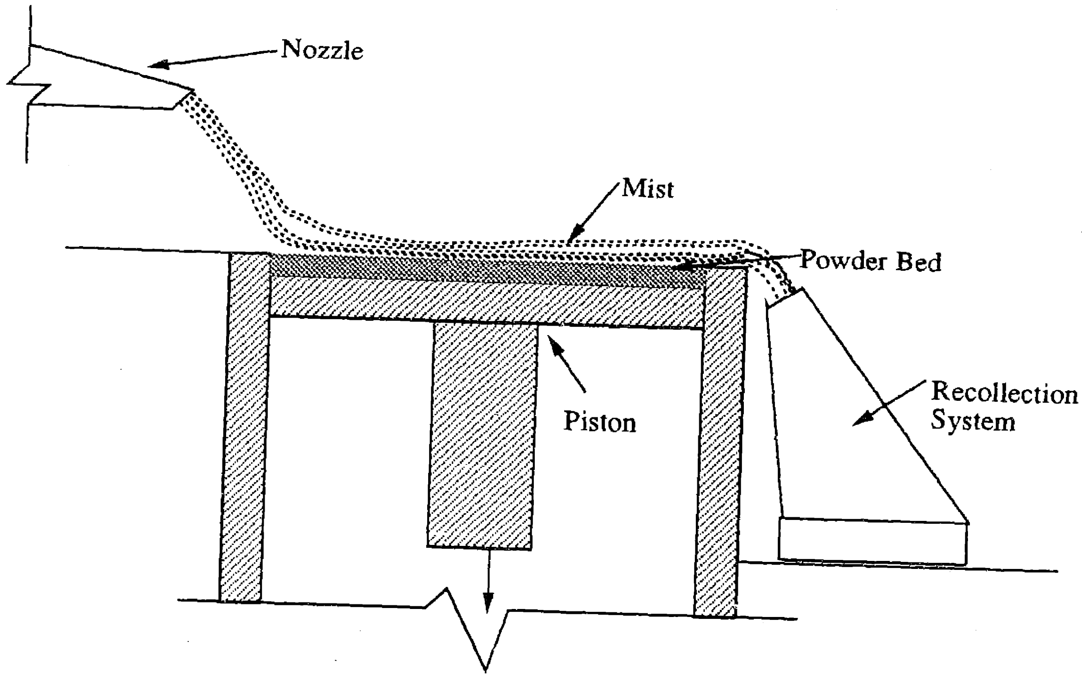


Figure 2-2: Ideal Moisture Flow

travel, and could remain uniform all through the area of the powder bed. That's why the vents were designed with long and narrow exits, so the flow was forced to travel across the whole width of the powder bed at the same time.

The vaporizer was tested with the first three vents, and the flow pattern was always highly irregular. The flow tended to go away from the powder bed, probably because it was hotter than the surrounding air and tended to rise. That's why further tests were not done with the vaporizer and it was discarded as a possible solution.

The ultrasonic humidifier was tested with all the vents. Testing was a building process: each vent design was based on the observations made with the previous arrangement. This tests didn't take into account the recollection system.

The first vent tested was the hose. The flow out of the hose didn't cover much of the powder bed area, and it passed very quickly over it. The hose was also hard to position.

The second system tested was the manifold. The main change sought with this design was to distribute the flow of the hose over the whole area of the powder bed. The actual flow coming out of the manifold was stronger through the openings right in front of the connection with the main hose, and very weak at the holes located near the ends of the manifold. The moisture covered a larger area, but not uniformly. The problem seemed to be the flow pattern after it had left the main hose.

An alternate solution tested was the array of individual thin hoses, all coming from the humidifier itself. This was supposed to distribute the flow across the whole area, plus do it uniformly since vapor coming out from each hose would have the same velocity. This solution didn't work either, because of the turbulence of the flow out of each hose, and the spaces left in between the hose exits.

The basic problem with these three previous arrangements was how the individual exits didn't provide uniformity of flow, but rather unique jet streams that changed direction constantly because of the turbulent flow, and never covered the powder bed at the same time. A nozzle that would concentrate the flow, forcing it to cover the powder bed without missing any spots because of individual openings, would be ideal.

The first nozzle tried was attached to the hose at its back, and it narrowed in one direction, but got wider in the direction perpendicular to the narrowing direction. (see Figure 2-3). Two alternatives were tried: uniform exit area, and variable exit area. The uniform exit area nozzle had the problem of not properly distributing the flow; most of it came through the middle, not covering the sides of the powder bed. The flow was also turbulent and uneven, so it wasn't satisfactory. With the variable exit area, the opening right in front of the hose was smaller than the opening at the sides (again, see Figure 2-3). This forced more moisture flow out through the sides, and consequently more of the powder bed was covered. The mist, though, sprayed out across the short sides of the powder bed, instead of just going from one long side to the other (straight across). This made it hard to collect with a system placed right opposite the nozzle. It wasn't a good enough solution.

There were some considerations as to the placement of the humidifier itself, too. It could be placed either in front of the machine (along the long side of the powder bed) or besides the machine (along the short side). The fifth alternative for a vent was a nozzle with the hose from the humidifier coming from the side. The nozzle is shown in Figure 2-4. It was shaped like a triangle (viewed from the side), with

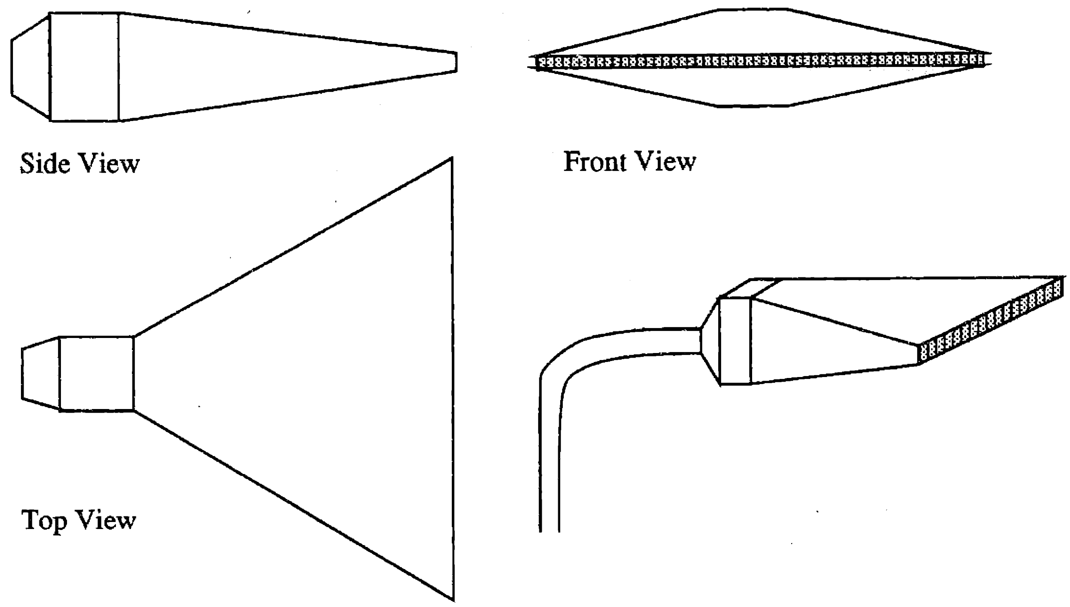


Figure 2-3: First nozzle

the connection with the hose in one of the triangular sides. This shape forced the moisture flow towards the powder bed, since the nozzle was held at some distance above it. The flow behavior for this configuration was also irregular; the flow from the hose shot straight through the nozzle, hitting the opposite wall, and the going out through the small exit area. There was more flow out at the far end of the exit area than closer to the hose, and it moved diagonally across the powder bed. The flow seemed to cover the whole area at some times, and other times it drifted towards one side or the other. Varying the exit area (from smaller were the strongest flow was to larger at the place were flow was weakest) improved the moisture flow a little bit, but it still didn't cover the whole powder bed uniformly.

The major problems being encountered were that the flow was not uniform, so it behaved irregularly going over the powder bed, and that the area to be covered was not being covered on its entirety. The hose seemed to be part of the problem: its cross-sectional area was smaller than the humidifier exhaust, so the flow coming out of the hose didn't fill out the nozzle, and it was hard to redirect the flow once it shot out of the nozzle, covering only a small area.

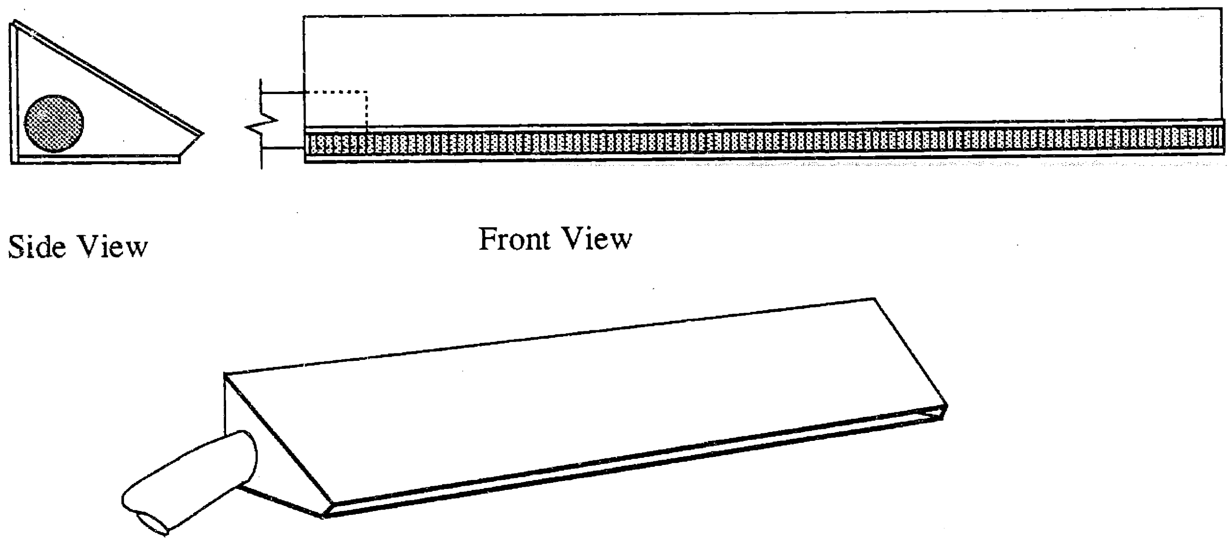


Figure 2-4: Second nozzle; flow from the side out through the front

Our last alternative proved to be the solution and it is described in detail in Chapter 3.

2.2 Recollection System

The second part of the problem was to collect the mist after it had wetted the powder, and redirect it out of the machine to keep it from damaging electrical and mechanical components. This recollection system had to resemble some sort of "vacuum cleaner" that would "suck down" the moisture flow, and redirect it out through a vent.

A custom-made "vacuum cleaner" could be made out of a small fan and a nozzle. Two fan sizes were tried:

1. a 3 1/8 inches square fan, with 12 watts

2. a 5 inches square, with 20 watts

Nozzles were attached to the fans (see Figure 2-5). The vents had to have a small area at the top to "concentrate" the vacuum, or the difference in pressures, that would direct the flow down the nozzle and into the vent. The design shown on Figure 2-5 was also part of the final solution, although modified.

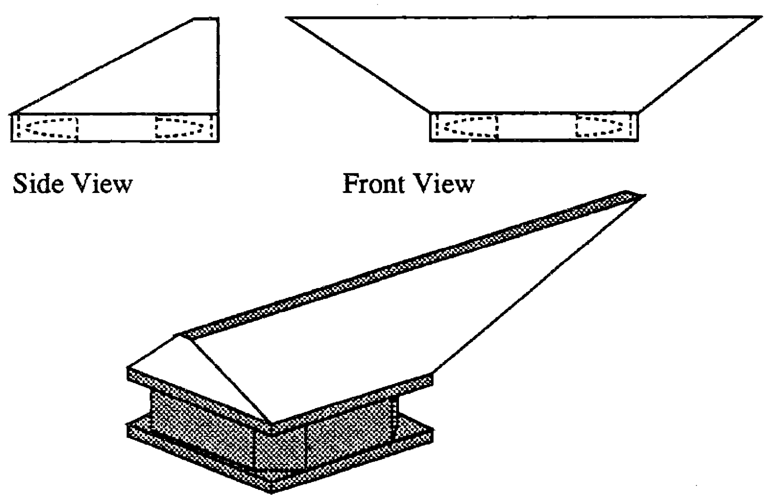


Figure 2-5: Vacuum Vent for the Recollection System

Chapter 3

Detailed Design of Humidifying System

The sixth type of vent tried proved to be the solution. It was called the nozzle-vent. The moisture flow out of the vent was laminar, and covered the whole area of the powder bed. It was also easy to direct (with "flaps"), so all parts of the powder bed were touched (the flow didn't sail over the powder). The vent was designed so it didn't interfere with any of the moving parts of the 3DP machine. The nozzle-vent was directly attached to the humidifier, in the first prototype, but it could easily be modified to be connected remotely to the humidifier (through a wide hose).

The sudden expansion at the exit of the humidifier slowed down the flow, and the pressure went up on the upper corner of the nozzle-vent. This difference in pressures drives the flow uniformly down the nozzle. The flow comes out at a higher velocity than the velocity at the upper corner, though, because of the narrowing cross-sectional area of the nozzle. Right after the exit the flow is laminar, so it stays uniform as it goes over the powder bed. The flow has enough momentum to make it across the powder bed, and it can be directed down towards the powder bed by the flap at the end of the nozzle (see Figure 3-3).

The recollection system consisted of the small fan (3 1/8 inches) and the vent shown on Figure 2-5, with modifications. Figure 3-4 shows the final design, with its dimensions. The 3DP machine would have to be redesigned to accommodate the fan.

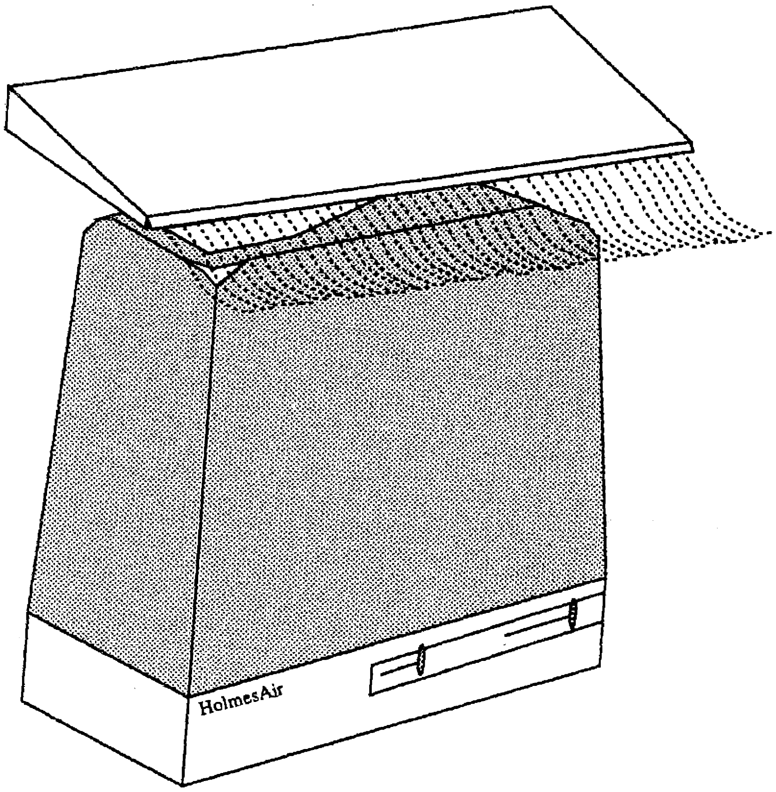


Figure 3-1: Nozzle-Vent; Isometric View

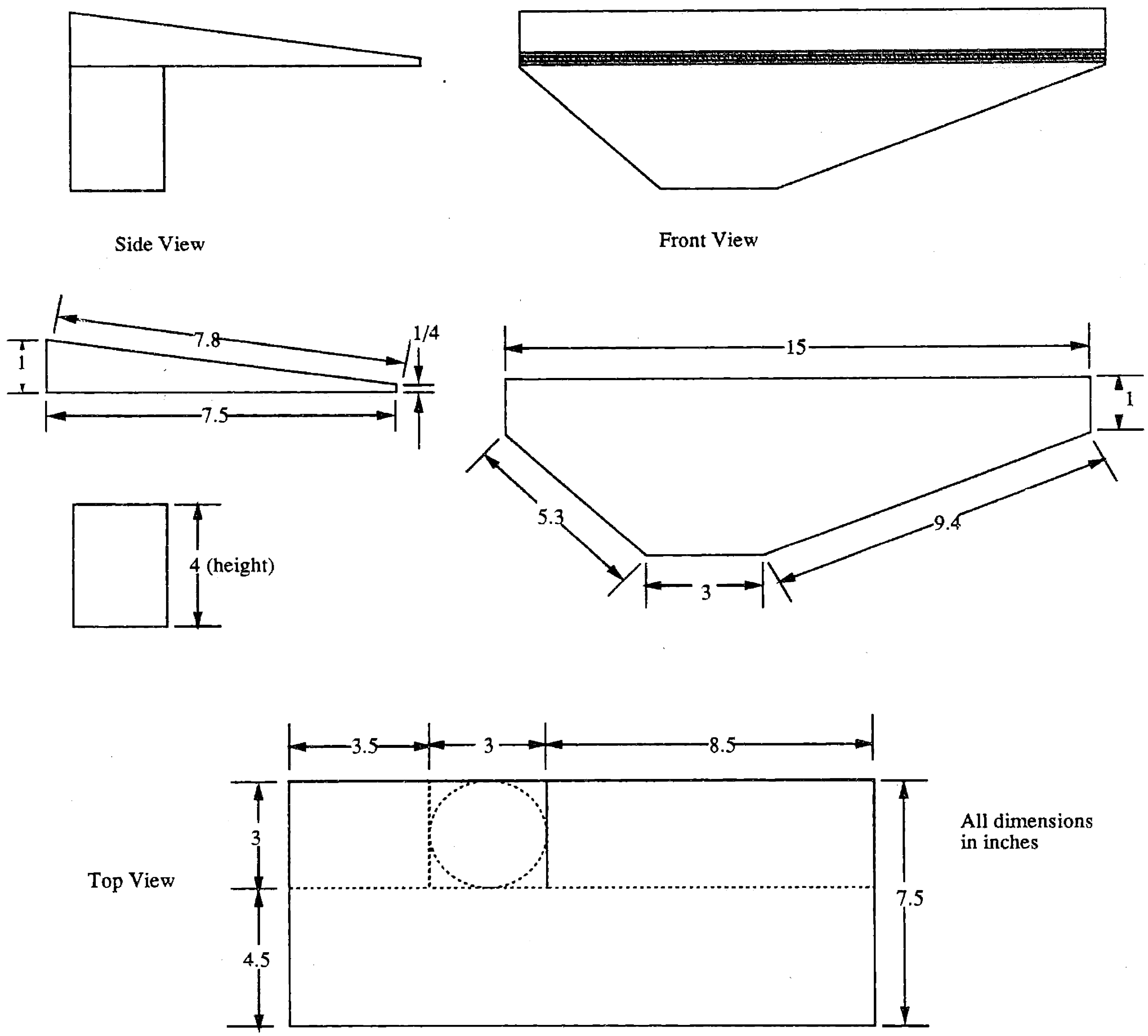


Figure 3-2: Nozzle-Vent; Dimensions

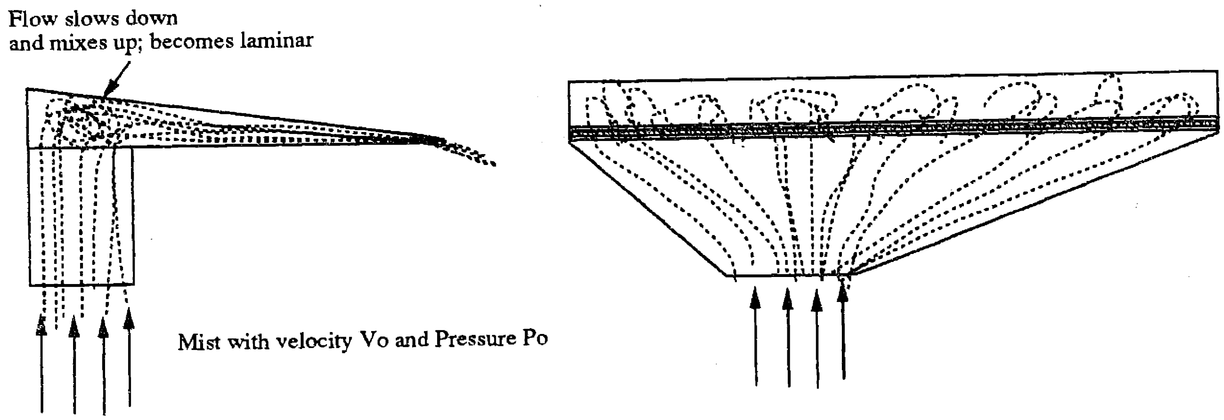


Figure 3-3: Moisture Flow Behavior

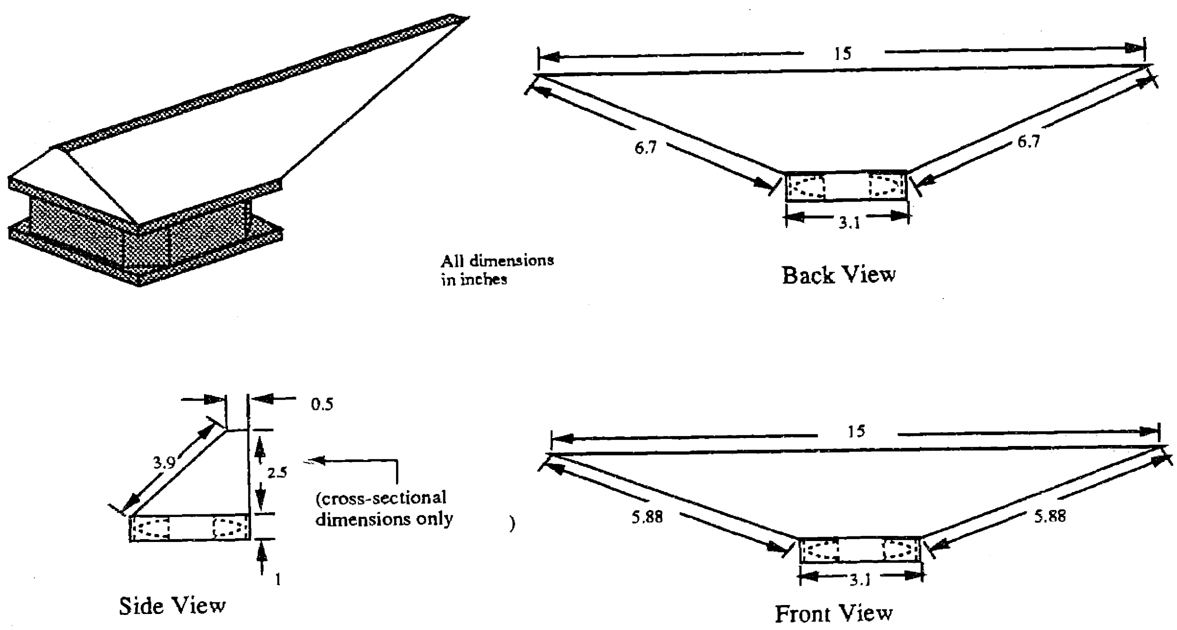


Figure 3-4: Vacuum Vent; Isometric View and Dimensions

Chapter 4

Conclusion

The humidifying system was tested on the 3DP machine, and it worked in terms of flow behavior and geometric compatibility. It remains to be tested on a real printing operation, and the surface roughness of any model printed with it has to be checked to see if there was any real improvement.

The design seems to be adjustable to different sizes of 3DP machines. On different machines the sizes will probably differ, but the basic principles of a sudden expansion at the opening of the humidifier, and then a narrowing nozzle of some length can be replicated quite easily. The placement of the humidifier can also vary, and the vent can be held fixed on the 3DP machine, while the humidifier is connected to the vent through a wide (3 inches diameter) hose.

There's an important parameter that has to be estimated and predicted for different layers of powder; the time it takes to completely wet a layer of powder is important to know, so the process of printing does not suffer any delays. We first assume that there's laminar flow; to see if this assumption holds true, we model the flow over the powder bed as incompressible flow over a flat plate. We check the Reynold's number for our moisture flow and check it against the Reynold's number for the transition from laminar to turbulent flow.

$$Re = \frac{\rho V_{out} L}{\mu} \tag{4.1}$$

$$Re_{laminar} < 10^5$$

For our system, $Re = 1.03 \times 10^4$. Our flow is laminar over the whole length of the powder bed. The parameters used for the calculation of our Reynold's number are listed in Appendix A.

The thickness of a powder layer is usually seven thousandths of an inch. This multiplied by the area of the powder bed (72 square inches) gives a volume of 0.504 cubic inches for a single layer. The layer could be close packed, with almost no empty space in between the powder grains, or it could have up to 50 % dead space. Assuming that wetting the whole layer means filling the dead space in the layer with water from the saturated vapor in the flow , we can establish an upper parameter for the time it takes to wet the whole layer by assuming that the whole amount of saturated vapor in the flow is deposited at any given time.

From measurements in the lab, we know that the rate of conversion of water into mist is 0.1 cm^3/s. This is the water flow rate, and is a fraction of the entire flow rate. We also know that the flow rate through the outer opening is 731 cm^3/s, assuming the flow takes up most of the volume of the vent. For 50% dead space, we calculated that it would take 41.3 seconds to wet the powder layer. Appendix A shows the parameters used for this calculation.

This analysis also tells us that for a bigger powder bed, we might need more than one humidifier, since the empty space might take two long to wet. Keeping the flow laminar wouldn't be too difficult, but the amount of moisture from one humidifier would take at least 183.6 seconds to wet a 90 percent packed powder bed, for example.

Another issue that remains is the motion of the printhead across the powder bed, and how it affects the moisture flow. The printhead tends to blow away the mist when it goes across the powder bed. This can affect the time it takes to wet the powder bed, as the mist is directed outside of the powder bed and it takes some time for the flow to return to its normal direction. The velocity of the printhead is approximately 60 inches/second. The flow field velocity is 12 inches/second, so it is 5 times slower than the printhead. The printhead travels about 20 inches, so it takes about 0.3

seconds for it to go across each time. Assuming each time it goes over the powder bed it blows the whole mist away, it would take the moisture 0.5 seconds to cover the powder bed again. If this is true, then after the printhead is on, the moisture flow would never make it across. Fortunately, the entire moisture flow doesn't get blown away by the printhead. There is still a problem with it, though, and there are two ways to fix it:

1. Increase the velocity at the exit of the humidifier by increasing the velocity of the humidifier's fan.

2. Start the moisture flow for some time before the printhead starts going across the powder bed (i.e. 10 seconds).

The last issue is condensation of the mist on the vents. On the recollection vent is not that much of a problem, but on the nozzle-vent, it can get to be enough to drip into the powder bed. To avoid this, the nozzle-vent will have Kapton flexible heaters attached to them, so condensation won't occur in the powder bed. The heat in the vent will prevent the water mist from condensing.

Appendix A

Parameters of Moisture Flow for Nozzle-Vent

For laminar flow over a flat plate:

$$Re = \frac{\rho V_\infty L}{\mu} < 10^5 \tag{A.1}$$

We know from measurements in the lab:

$$V_{humidifier} = 6.29\ in/s$$

$$Q_{water} = 6.1 \times 10^{-3} in^3/s$$

The velocity was measured by averaging ten measurements of the time it took for the tip of the mist to travel 6 inches after the flow was fully developed. The water flow rate in the mist was measured by measuring how much water volume (from the weight) was used up by the humidifier over 10 hours and 12 minutes of use.

From continuity: $V_2 = V_\infty = 11.9\ in/s$ right at the exit of the nozzle vent. From tables:

$$\rho = 5.5 \times 10^{-5}\ lbm/in^3$$

$$\mu = 3.8 \times 10^{-7}\ lbm/in - s$$

The density ρ is part air $(1 - 1.37 \times 10^{-4})$ at 32 degrees Fahrenheit plus the density of saturated water ($62.4\ lbm/in^3$) times the fraction of water in the full flow rate (1.37×10^{-4}). The length of our powder bed is $L = 6in$.

This gives us $Re = 1.03 \times 10^4$ so the flow is laminar.

To calculate the time it takes to wet the powder layer, we assume that the entire $6.1x10^{-3}$ cubic inches/second wet the powder layer, so it is just a matter of dividing the volume of empty space by this flow rate of the water in the moisture flow .

$$\frac{0.252\ in^3}{6.1 \times 10^{-3}\ in^3/sec} = 41.3sec.$$