Study of the Refrigeration Characteristics of a Vortex Heat Exchanger

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Abstract

The refrigeration characteristics and governing parameters of a vortex heat exchanger were studied in this investigation. A set of empirical curves was developed utilizing input variables of inlet pressure, flowrate, and diffuser gap distance. A temperature profile of the bottom diffuser plate was obtained using an infrared camera. It was found that as the inlet pressure increases, the temperature drop across the vortex heat exchanger also increases. The optimum diffuser gap distance was determined to be 0.254 mm.

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Introduction

As electrical and mechanical systems undergo normal operation, they generate heat. To remove this heat, many different types of refrigeration systems have been employed. The most effective refrigeration process is the adiabatic expansion of a gas with external work, which may take place in a reciprocal engine or in a turbine. This refrigeration system is mechanically complex especially in the low temperature region. A much simpler throttle-effect is utilized in the Joule-Thomson cooler which does not require any moving parts. This refrigerator, however, is easily clogged and requires high pressure operation which causes poor system reliability. Desirable refrigeration system qualities that these systems do not provide include low weight, high reliability, and reduced cost (EXAIR). All of these are characteristic of the vortex heat exchanger.

A vortex heat exchanger is a standard Ranque-Hilsch tube that has been attached to a diffuser (see Fig. 1) (Nash, 1975). Although the principles of the vortex tube have been known for over 20 years, it is only recently that the effects of the addition of a diffuser have been encountered. In this arrangement, compressed air is permitted to enter through a tangential nozzle into a cylindrical container. A turbulent flow of gas, in a helical motion, passes down the tube in the form of a spinning shell. A valve at one end of the tube allows a fraction of the air to escape as hot exhaust. The remaining air flow is forced back down the tube as a second vortex inside the low pressure area of the larger vortex. This inner vortex loses heat and exhausts radially outward through the diffuser plates located on the opposite side as cold air (see figure 2). One report on a comparable apparatus has shown that for inlet conditions of 21.5 C and 3 atm. pressure, a core temperature of -77°C could be obtained (Nash, 1973).

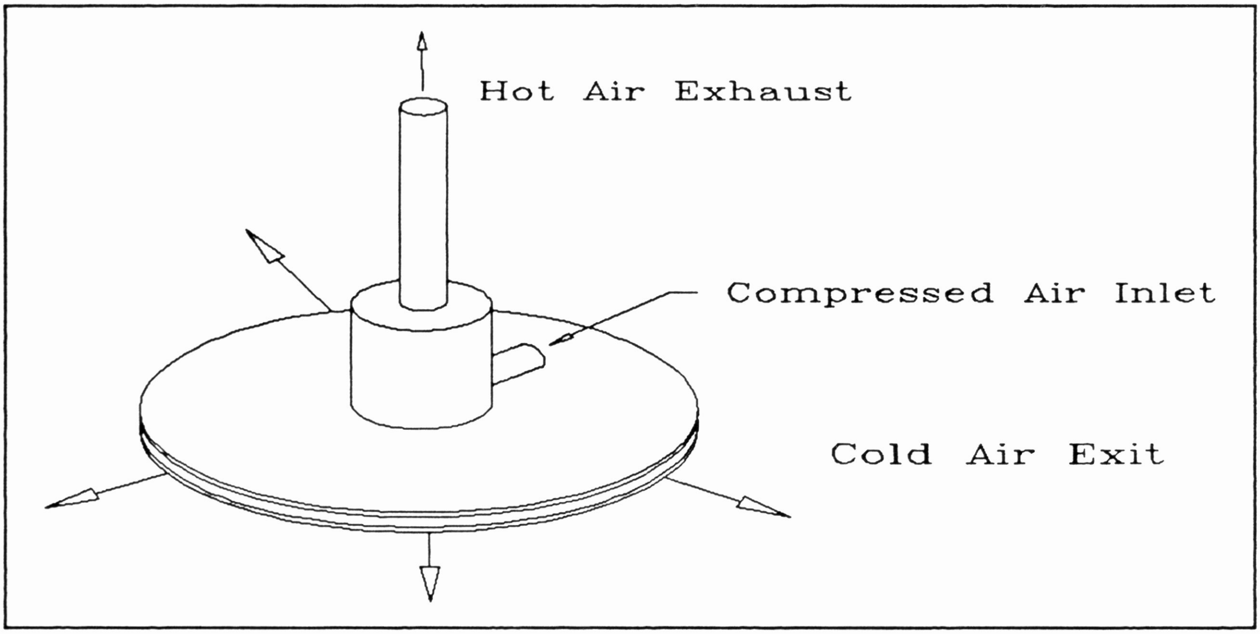


Fig. 1: Vortex Heat Exchanger

Theory

Theories abound regarding the dynamics of the vortex tube. There is, however, a widely accepted qualitative explanation of the phenomena. This description was made by Hilsch (1947) in his pioneering paper where he postulated an outward flow of kinetic energy due to internal friction. This is based on an assumption that the velocity profile of the entering air was a portion of a free vortex. As the air moves towards the hot valve, shown in Fig. 2, the velocity profile is converted to that of a forced vortex by the action of viscosity. Thus, angular momentum has been lost from the inner vortex in the form of kinetic energy to the outer vortex.

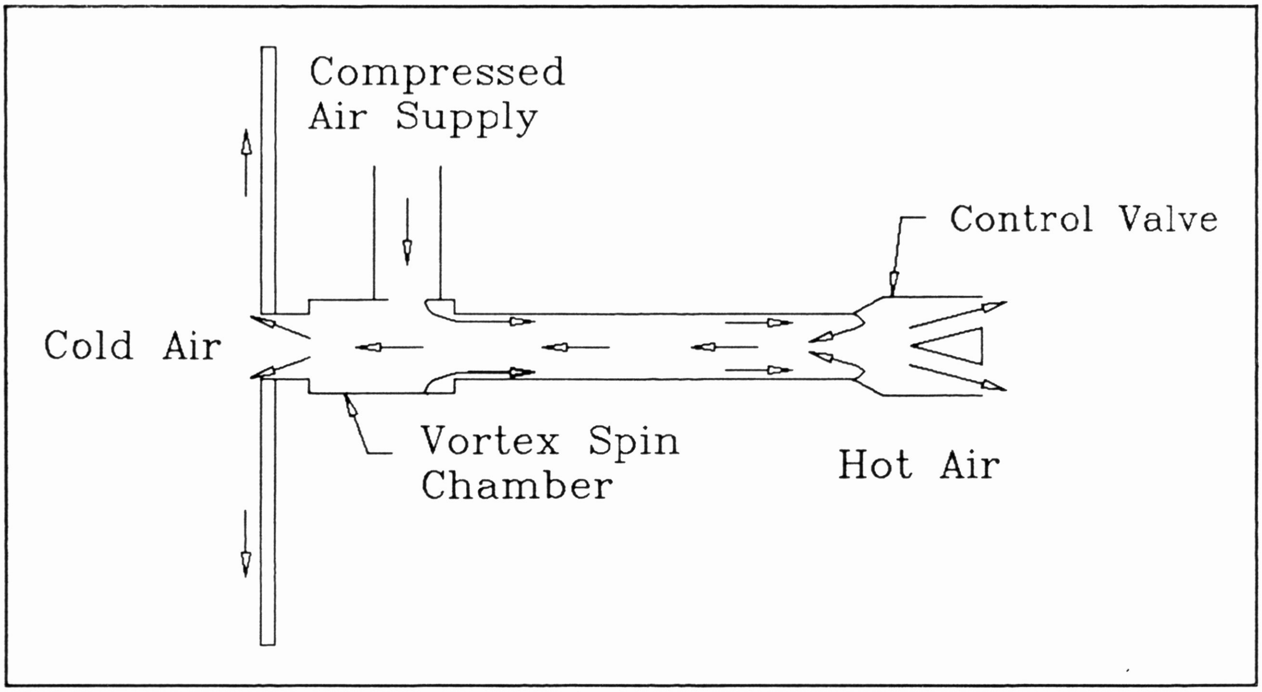


Fig. 2: Vortex Heat Exchanger Cross-section

This transfer of energy is in conjunction with the expansion process undergone by the flow medium causing a reduction in temperature of the inner vortex.

The limitation of this refrigeration process is the outlet pressure which is equal to ambient pressure in a standard vortex tube. In a vortex heat exchanger, the addition of a diffuser allows the core pressure at the cold exit to drop below atmospheric pressure. This is due to a combination of conservation of mass and energy. A lower pressure results in more expansion and a lower temperature than was previously possible.

The effect of the addition of a diffuser to the standard vortex tube can best be illustrated by the temperature-entropy diagram for air shown in Fig. 3. The inlet condition is represented as point A. Expansion through a vortex tube is shown as the curve A-C where the limitation of the cooling effect is the outlet pressure. Expansion through a vortex cooler results in the curve A-C-E. This is because the pressure at certain portions between the diffuser plates is allowed to fall below atmospheric pressure (Nash, 1975).

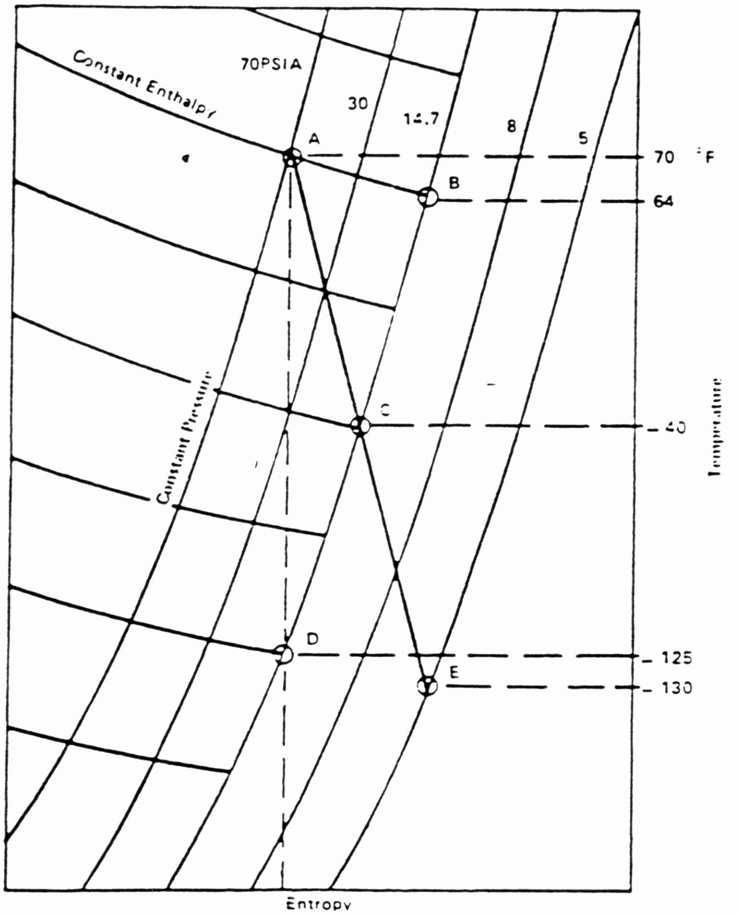


Fig. 3: Temperature Entropy Diagram

Objective

The objective of this research was to study and analyze the refrigeration characteristics and governing parameters of a vortex heat exchanger. This involved three phases including physical modeling, experiment and data acquisition, and analysis. This research provided a range of experimental data on the refrigeration effects of a vortex heat exchanger in the form of empirical temperature performance curves.

Scope and Limitations

Although there have been several other investigations concerning the addition of a diffuser to a vortex tube, these have been mainly theoretical in nature and have focused on the vortex helical flow. The present investigation provides empirical curves of the bottom diffuser plate temperature with inlet variables of pressure, flowrate, and diffuser gap distance. Pressure and flowrate do not vary independently in this experiment. Because the temperature was measured at the bottom diffuser plate which was 2.16 mm thick, the temperature of the air flow is not known or determined.

Report Organization

The following report entails a discussion of the test apparatus and procedure, followed by results, summary of the findings, and observations from which conclusions were made.

Lastly, recommendations were offered for future actions to be taken.

Experimental Apparatus

The experimental apparatus consisted of several parts: the aluminum test apparatus, a vortex tube, a plexiglass diffuser plate and an aluminum diffuser plate, two rotometers, a pressure regulator, an air filter, a thermocouple, and an infrared camera. The experimental apparatus is illustrated in Fig. 4.

The aluminum test apparatus was designed specifically to accommodate the vortex tube and all varying parameters. The bottom plate was 33 cm in diameter. This is for stability as well as a platform to mount the infrared camera on. Three solid 2 cm rods 51 cm in length were mounted on the bottom plate. The length of the rods ensured a proper distance for the focal length of the infra-red camera. The top plate was also 33 cm in diameter with a 3.8 cm diameter hole in the center and mounted on top of the three aluminum rods. A plexiglass diffuser plate 7.5 cm in diameter was suspended from the top plate by three small pieces of all-thread each encompassed by a 3.8 cm long spacer. The vortex tube was placed down through the hole in the top plate and screwed into the plexiglass diffuser plate. A 23 cm diameter plate was then attached below the diffuser plate to the top plate with three finely thread screws. This plate had a 7.6 cm diameter raised hole in the center of it which provided support to rest the bottom aluminum diffuser plate on. This design allowed for varying diffuser plate distances and did not interfere with flow between the plates. The bottom diffuser plate was 7.5 cm in diameter and was painted black on the bottom side for clarity in distinguishing it from the aluminum apparatus when utilizing the infrared camera.

A Hughes Probeye 3000 Thermal Imaging system was used, and was attached to a monitor for viewing purposes. This system was also attached to a color television screen and VCR for additional reviewing purposes. The air filter utilized was an Arrow air line filter series F35 with maximum pressure rating of 36.25 kPa. The Arrow air line pressure regulator series R35 was used and had a maximum supply pressure of 43.5 kPa. The vortex tube was an Exair vortex tube model number 3402 with an air consumption of 0.056 cm^3/min at 14.5 kPa inlet pressure.

Referring to the schematic in Fig. 4, the compressed air, which was supplied from a feed line source in the laboratory, entered the ball valve, flowed through the air filter and was controlled by the regulator while the pressure was read before entering the rotometer where the flow rate was recorded. The air then traveled into the vortex tube where the hot exit flow rate was monitored by another rotometer, and the cold air exit escaped between the two diffuser plates. The infrared camera was mounted on the bottom test apparatus plate and focused on the bottom diffuser plate. The image produced by the camera was visualized on a color television monitor and recorded on VHS VCR tape. The ambient temperature was also measured by a thermocouple located at the inlet to the vortex tube.

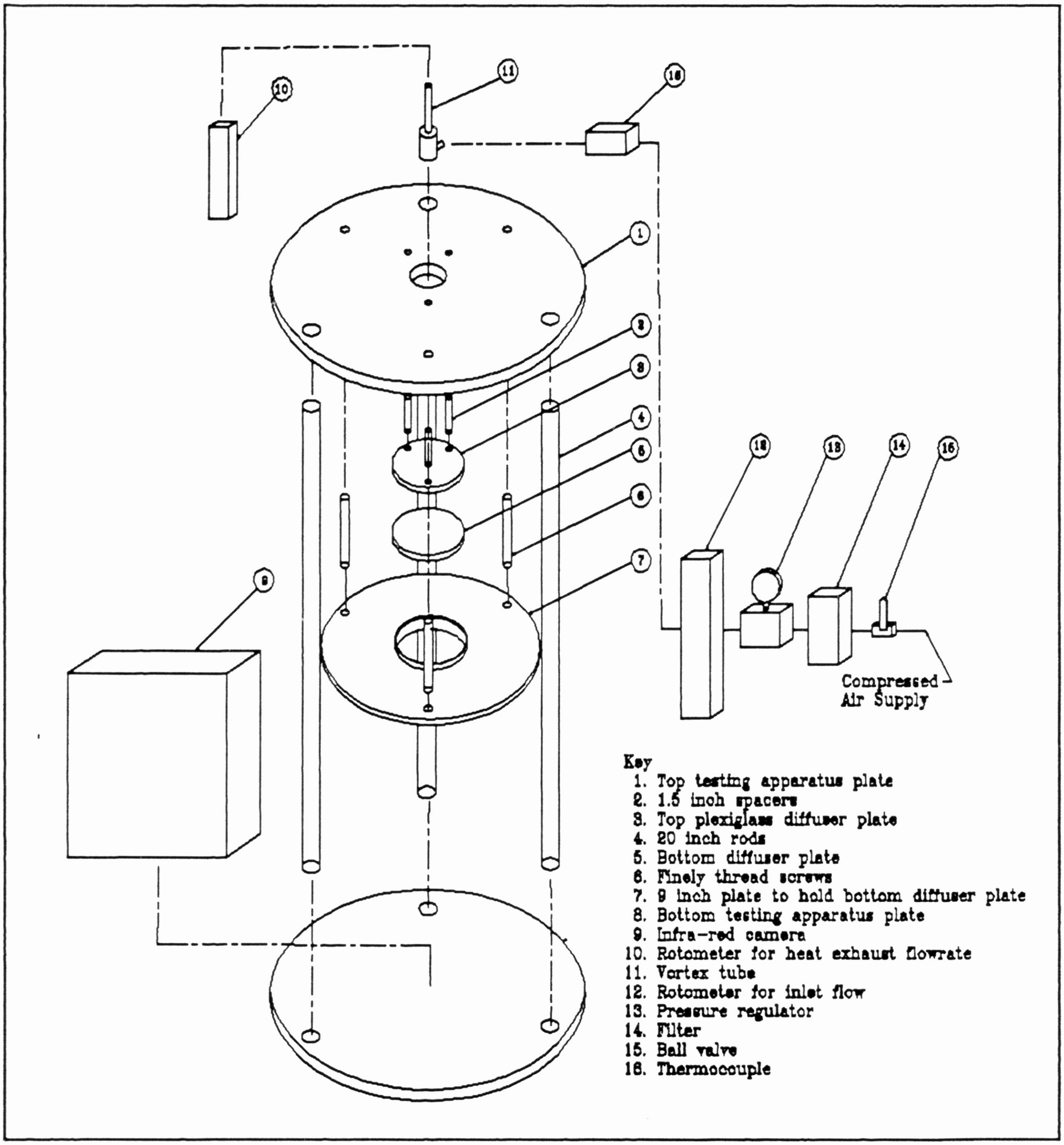


Fig. 4: Experimental Apparatus Schematic

Experimental Procedure

The method for data acquisition was determined initially then improved upon through a trial and error process. The following is the finalized experimental procedure utilized for this research.

First, the diffuser plate gap distance was set to the required displacement taking care that the diffuser plates were perfectly level. This was accomplished utilizing a caliper and the three small holes drilled into the top plate. The diffuser plates were tightened together until there was no gap, then the distance between the top plate and the plate that supports the bottom diffuser plate was measured. The three fine thread screws were loosened to the desired gap width using the first set of measurements as a reference point. Because the diffuser gap distances varied from 0.127 mm to 0.889 mm, accuracy was very important. The compressed air supply was turned on and the inlet pressure was adjusted to the desired position using the pressure regulator. The two rotometers were checked to make sure that the hot exit value of the vortex tube was releasing 80% of the total flow. This flowrate percentage was determined to be optimum in providing the lowest temperature by several reports as well as the vortex tube manufacturer's guide (EXAIR). If the measured flowrate was not correct, the vortex valve was adjusted accordingly.

The bottom diffuser plate was allowed to reach thermal steady state. This was typically 20 minutes. Then the infrared camera and VCR were turned on to begin taking data. A round, symmetrical temperature profile appeared on the screen. This was the bottom diffuser plate. By moving the cursor of the camera in increments of 4.2 mm (guided by the grid on the screen) across the temperature profile, each individual temperature was visualized. Holding the cursor on each point 30 seconds, a consistent reading was insured. Finally, the pressures, both flowrates, and the ambient temperature from the thermocouple were recorded.

This was the standard procedure followed throughout the experiment. The independent parameters that changed included diffuser gap distance and inlet pressure. The temperature readings recorded by the infrared camera were of the bottom side of the lower diffuser plate and were only accurate to the extent that the emissivity was correctly predicted. Therefore, the purpose of the temperature profiles was not to record the coolest temperature obtainable, but to observe the relative optimization and cooling characteristics of the heat exchanger.

Results

Temperature Difference Variation with Pressure

There was a very consistent trend that occured when a diffuser gap distance was held constant and the inlet pressure and flowrate were varied simultaneously. As the pressure increased, the temperature difference between the inlet or ambient air and the bottom diffuser plate temperature also increased. An example of this can be seen in Figs. 5 through 10. At constant diffuser gap distances of 0.127 mm, 0.254 mm, 0.381 mm, 0.508 mm, 0.635 mm, and 0.889 mm, the pressure was varied from 3.6 kPa to 5.8 kPa in increments of 0.73 kPa. The four curves on each figure demonstrated that the larger the pressure, the cooler the bottom diffuser plate.

The pressure was measured on a pressure regulator with an analog scale in divisions of

0.73 kPa. Therefore, the uncertainty associated with this reading was 0.36 kPa. The temperature from the infrared camera was read to the nearest 0.1°C digitally.

Temperature Difference Variation with Diffuser Gap Distance

The trend that was consistently observed in the results was that a diffuser gap distance of 0.254 mm results in a larger temperature drop than all other diffuser gap distances tested. Gap distances of 0.127 mm to 0.889 mm in increments of 0.127 mm were used in this experiment.

With only a few exceptions or overlapping, a trend was also observed of all other experimental diffuser gap distances. They were listed in order from producing the greatest temperature drop to the smallest temperature drop. This listing was as follows, 0.254 mm, 0.381 mm, 0.127 mm, 0.508 mm, 0.635 mm, 0.889 mm. Figs. 11 through 14 are visual examples of this ranking. Each of these figures represented a constant pressure from 3.6 kPa to 5.8 kPa. The diffuser gap distances on each figure were varied.

As mentioned above, there was some discrepancy in the ranking of diffuser gap distances. Holding the pressure constant and as the diffuser gap reached 0.508 mm or larger, the temperature differences were so similar that 0.635 mm at times produced a lower temperature at the diffuser plate center than 0.508 mm. This seemingly inconsistent behavior could be a result of two actions. First, the method used to determine the gap distance could have been a cause. As detailed previously in the experimental procedure, the method to measure the gap distance utilized a caliper and relative distance measurements. The caliper was accurate to

0.0254 mm. Because relative distance measurements were used, the thickness and smoothness variations in the testing apparatus surfaces should not be a factor. Therefore, fault in the measuring scheme would be of human error. This was possible as the caliper was used to measure depth and must be perfectly level and straight through a distance of 6.6 cm. This distance was from the top testing apparatus plate to the top of the nine inch plate that held the bottom diffuser plate as shown in Fig. 4.

The second possibility for the overlapping temperature profiles of different diffuser gap distances in excess of 0.381 mm was that once the gap becomes larger than 0.381 mm, the temperature profile becomes less sensitive to the distance between the diffuser plates. This possibility was supported by the similarity of temperature achieved by diffuser gap distances of 0.508 mm, 0.635 mm, and 0.889 mm as seen in the above mentioned Figs. 11 through 14.

Temperature Profile Variation With Identical Input Variables

Figs. 15 through 18 show curves holding both pressure, flowrate, and diffuser gap distance constent. The data for each curve was taken on different testing days throughout the duration of the research. The purpose of these curves was to determine the consistency with which data was obtained using the previously discussed testing apparatus and method.

As seen in the above referenced figures, the temperatures obtained from identical initial conditions were very comparable. The deviation had a range of 0.3°C at the center of the diffuser plate. These figures were the best representative of the relative accuracy of this experiment. Therefore, the relative uncertainty of the temperature profiles was 0.3°C at the center of the diffuser plate.

Temperature Dependence on Pressure

Figs. 5 through 7 show varying pressures with a constant diffuser gap distance of 0.254 mm, 0.381 mm, and 0.127 mm. As the pressure increased, the temperature difference between the profiles also became larger. This was not a constant dependence, nor did it appear to be linear. The lower pressures of 3.6 kPa and 4.4 kPa were close together with a temperature difference at the center of the diffuser plate of approximately 0.3°C to 0.4°C. As the pressure was increased to 5.1 kPa and 5.8 kPa, the temperature difference between the profiles was approximately 0.8°C to 0.9°C. This could indicate that the temperature difference versus pressure at a constant diffuser gap distance reached a steady state or constant value as the pressure was increased beyond 4.4 kPa. There was not, however, enough data at high pressures in this investigation to support this possibility.

Figs. 8 through 10 show varying pressures with constant diffuser gap distances of 0.508 mm, 0.635 mm, and 0.889 mm. At lower pressures of 3.6 kPa and 4.4 kPa, the curves were very close together. The temperature difference separating the temperature profiles was approximately 0.1°C to 0.2°C. As the pressure increased to 5.1 kPa and 5.8 kPa, the temperature difference separating the profiles also became larger. The temperature difference between 4.4 kPa and 5.1 kPa was approximately 0.9°C. Between 5.1 kPa and 5.8 kPa, however, the temperature difference was approximately 0.6$_{o}$C to 0.7°C. The relationship between pressure and temperature difference at a constant diffuser gap distance first increased then decreased. This contrasted with the above relationship for diffuser gap distances of 0.127 mm to 0.381 mm.

It was seen in this investigation that the increase in pressure would result in an increase in temperature difference, or a lower outlet temperature. From the experimental data taken in this research, however, one cannot predict how much effect increasing the inlet pressure to the vortex heat exchanger would have on the outlet temperature at a constant diffuser gap distance beyond the data points tested.

Temperature Drop Across the Diffuser Plate

Each temperature profile presented showed a temperature differential between the outside of the diffuser plate and the center of the diffuser plate. This temperature difference was in a range of 0.5℃ to 1.8°C. The shape of the temperature profile did not appear to be a function of pressure or diffuser gap distance, although a clear relationships were difficult to determine.

The relatively large temperature differential from center to edge of the diffuser plate could have been a result of a pressure differential existing in the flow between the two diffuser plates. In this instance, the lower temperature at the center of the diffuser plates could have been indicative of a lower pressure. The actual pressures in between the two diffuser plates, however, were unknown in this investigation.

Another possible contributing factor was that the diffuser plates are open to the atmosphere and ambient air temperature. The heat from the surroundings could have contributed to the higher temperatures at the edge of the diffuser plate.

Fig. 5: Temperature Profile at a Diffuser Gap Distance of 0.127 mm.

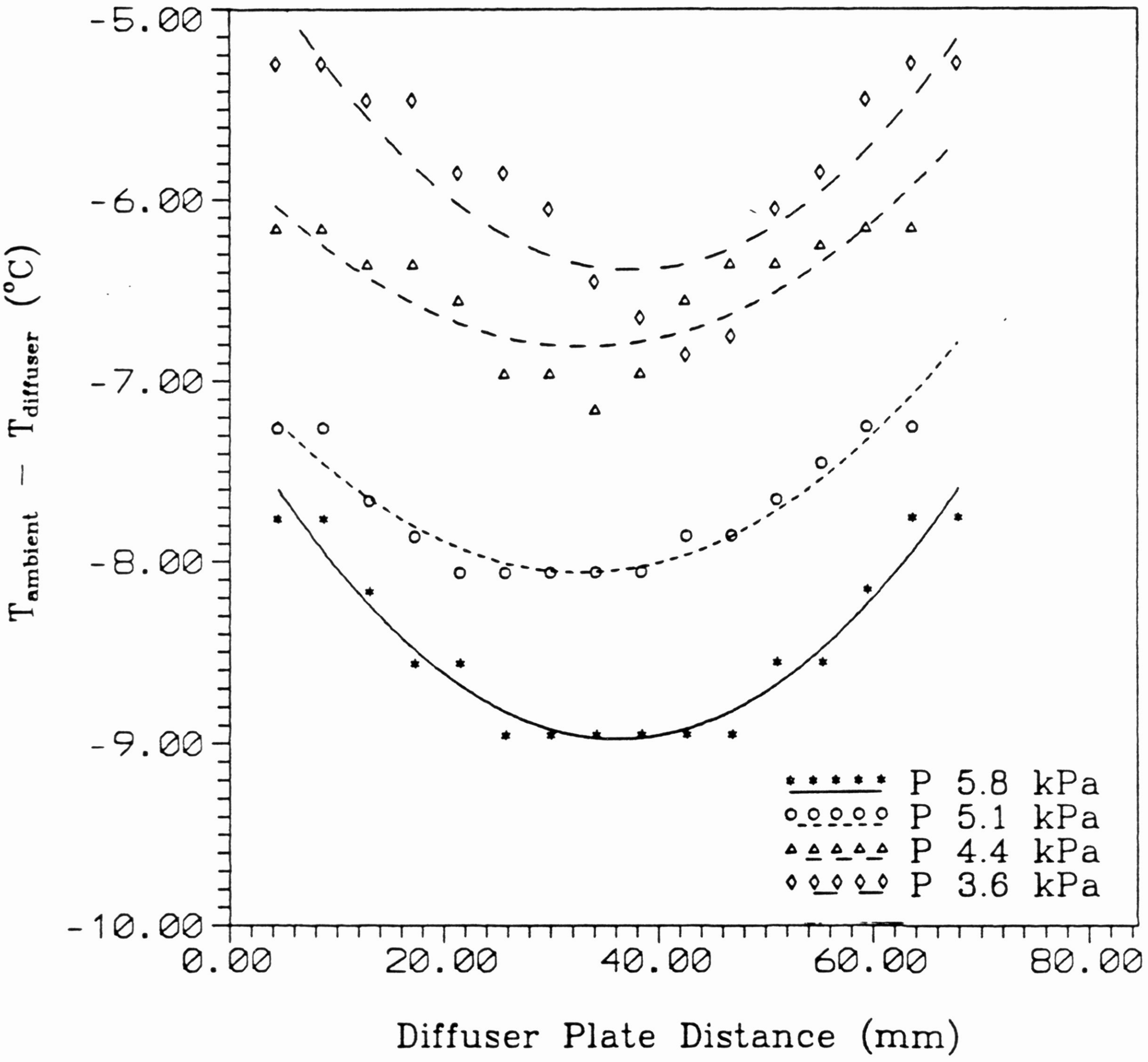


Fig. 6: Temperature Profile at a Diffuser Gap Distance of 0.254 mm.

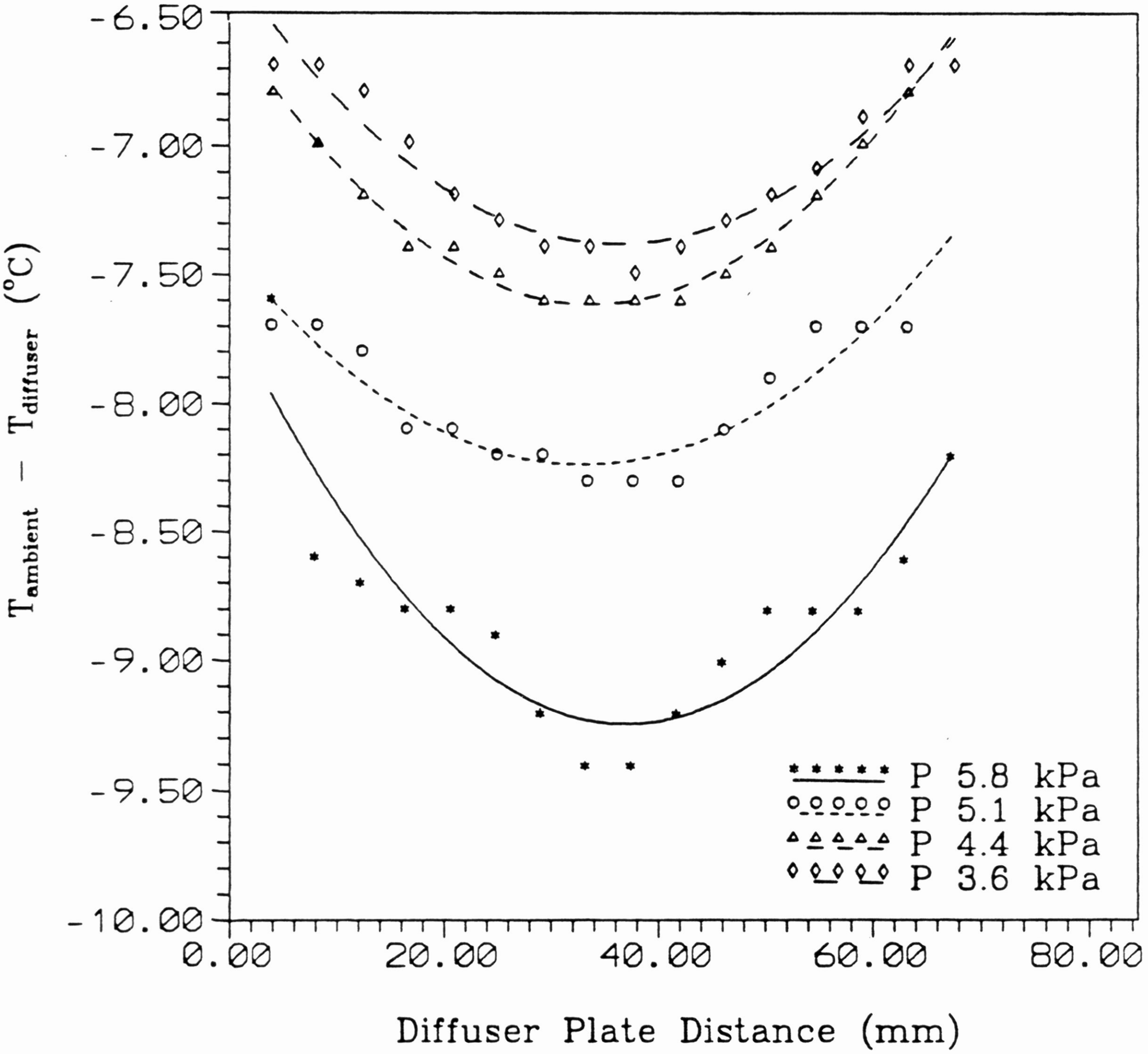


Fig. 7: Temperature Profile at a Diffuser Gap Distance of 0.381 mm.

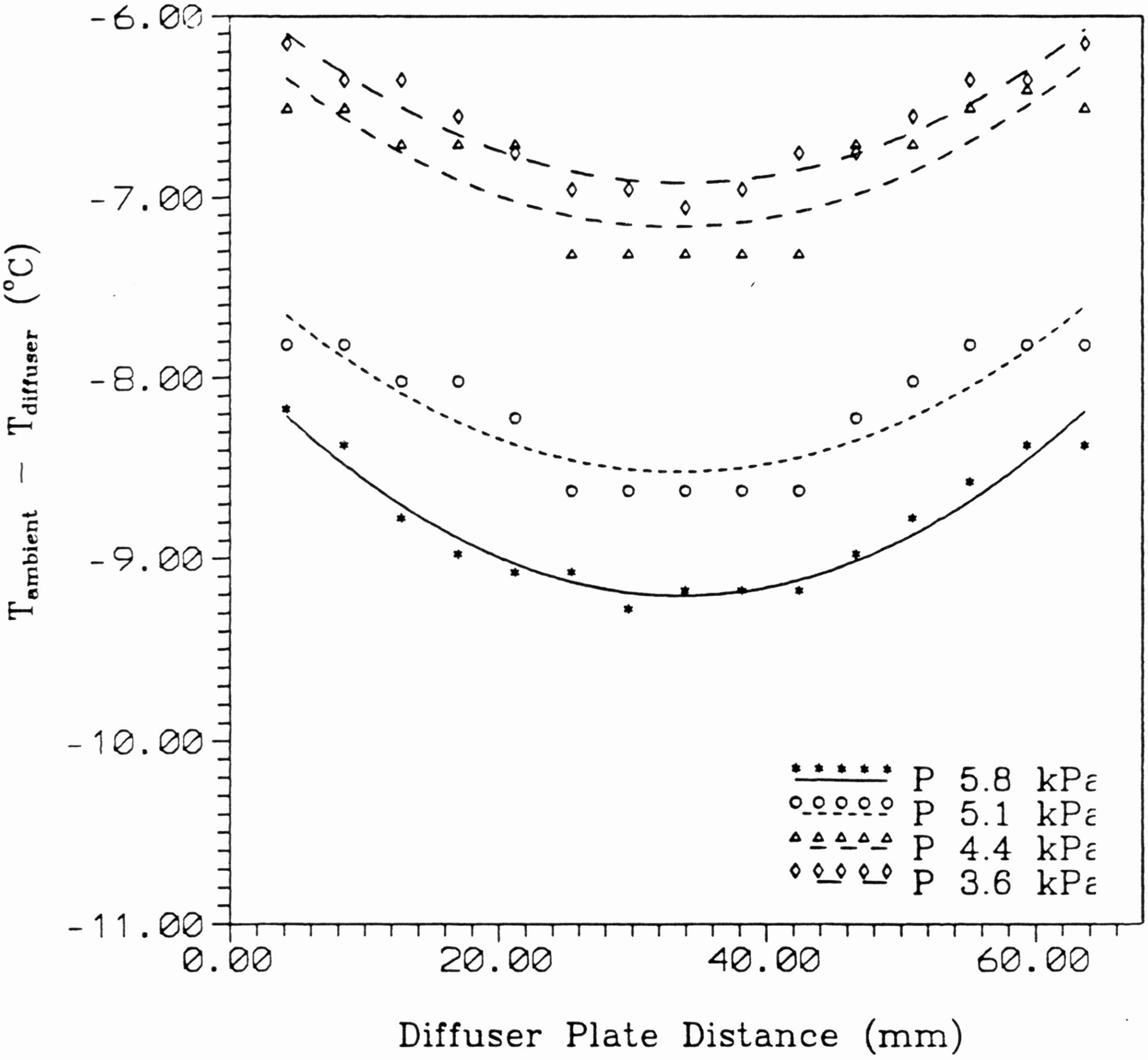


Fig. 8: Temperature Profile at a Diffuser Gap Distance of 0.508 mm.

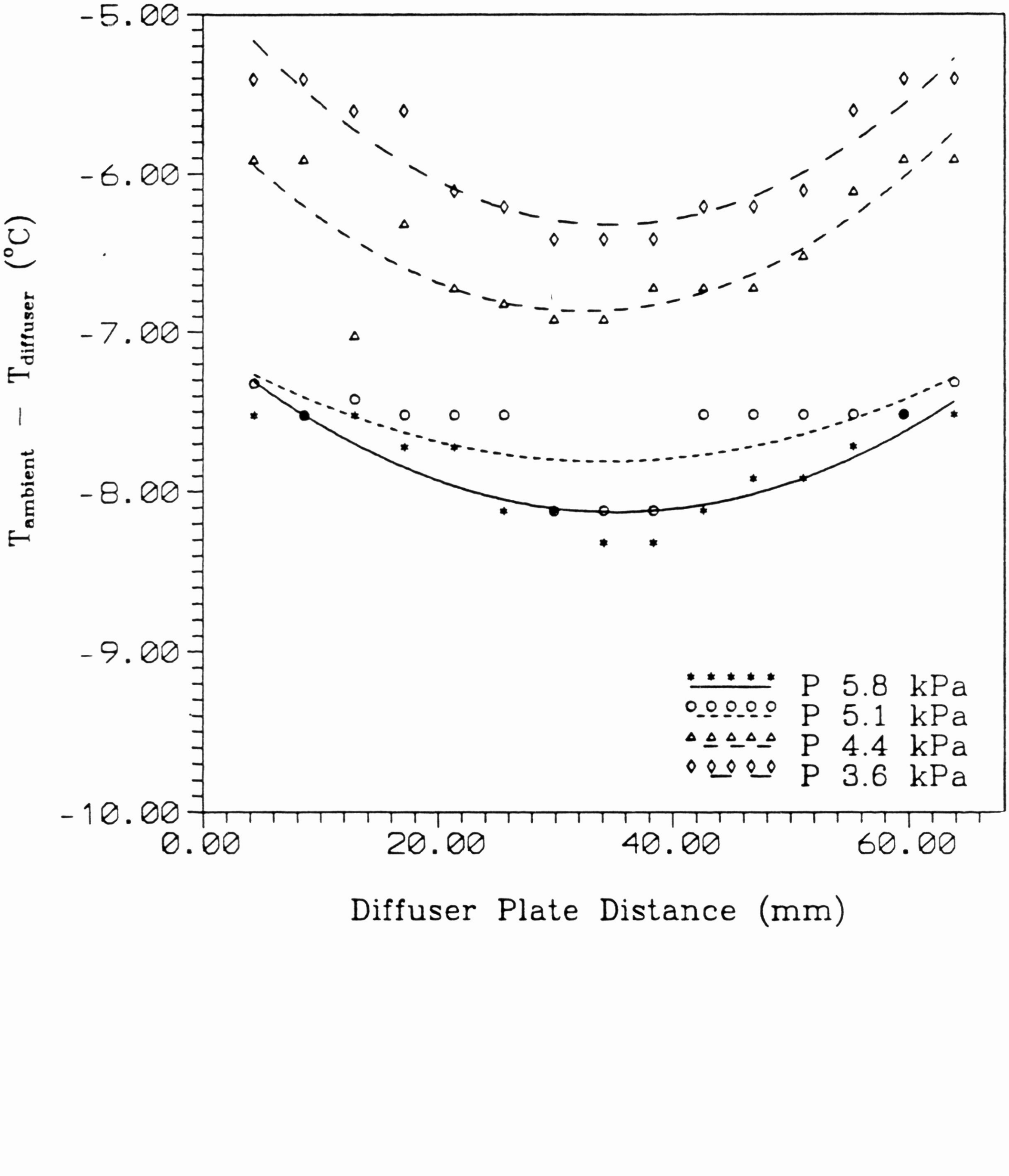


Fig. 9: Temperature Profile at a Diffuser Gap Distance of 0.635 mm.

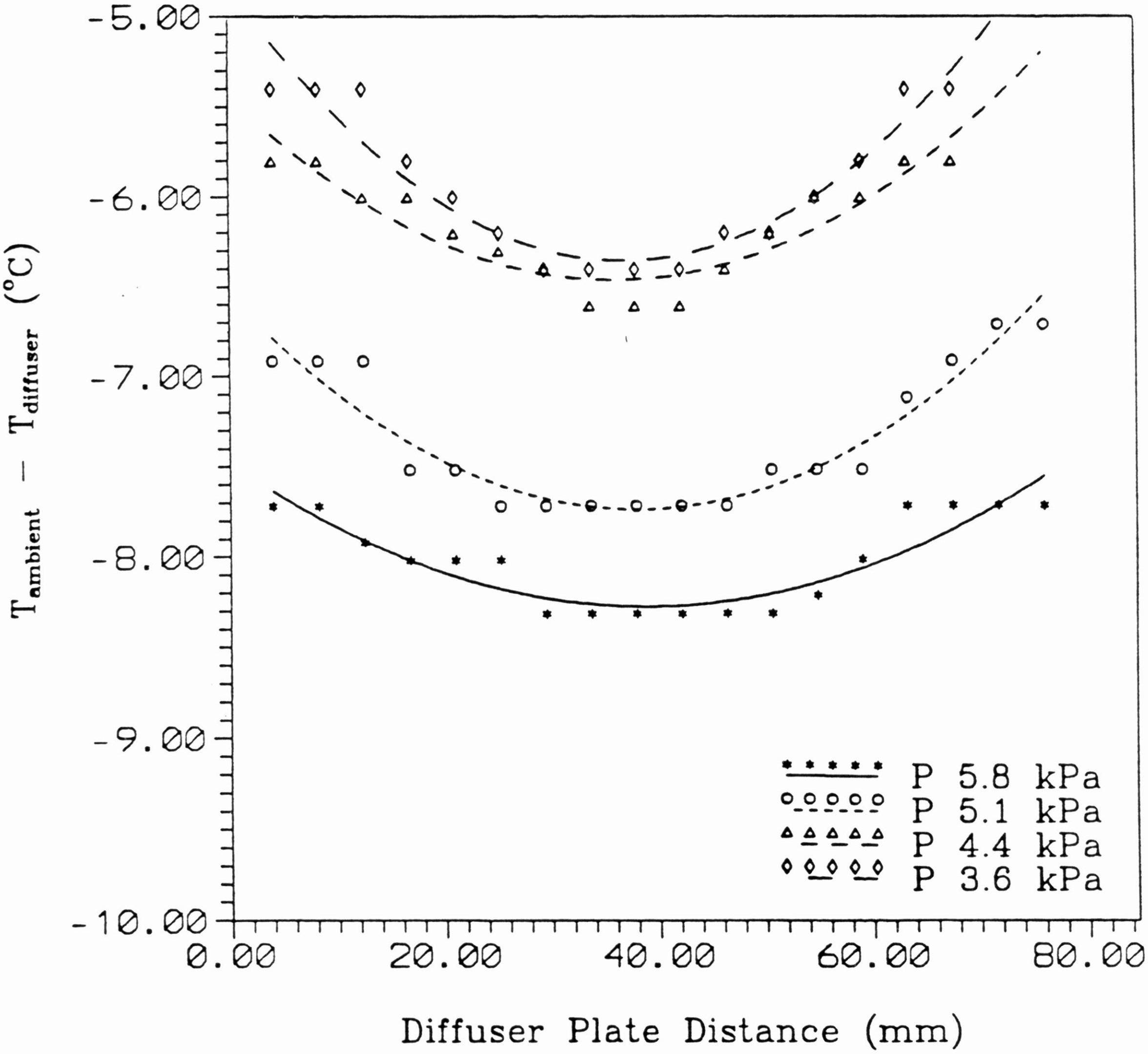


Fig. 10: Temperature Profile at a Diffuser Gap Distance of 0.889 mm.

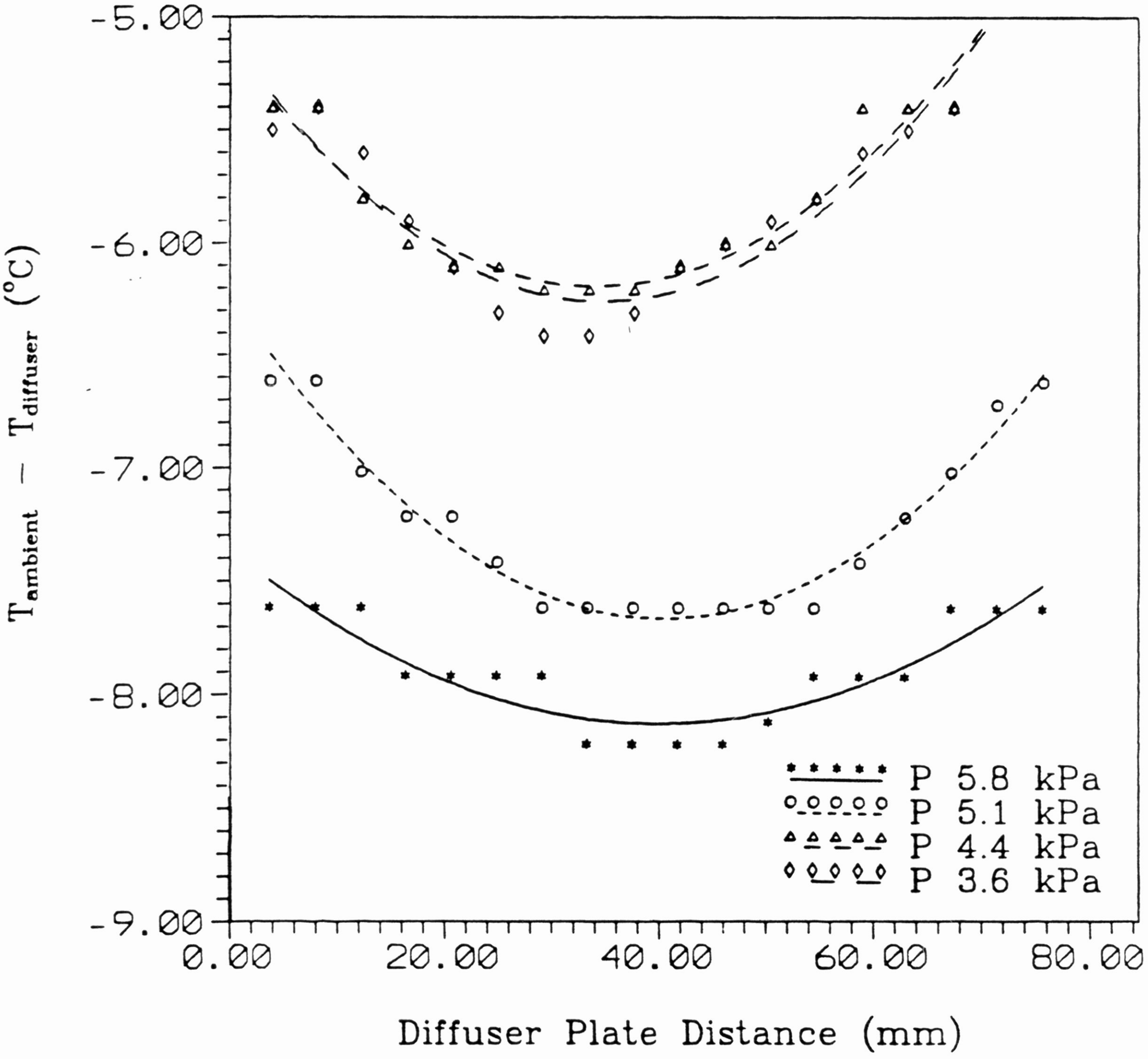


Fig. 11: Temperature Profiles at a Pressure of 5.8 kPa.

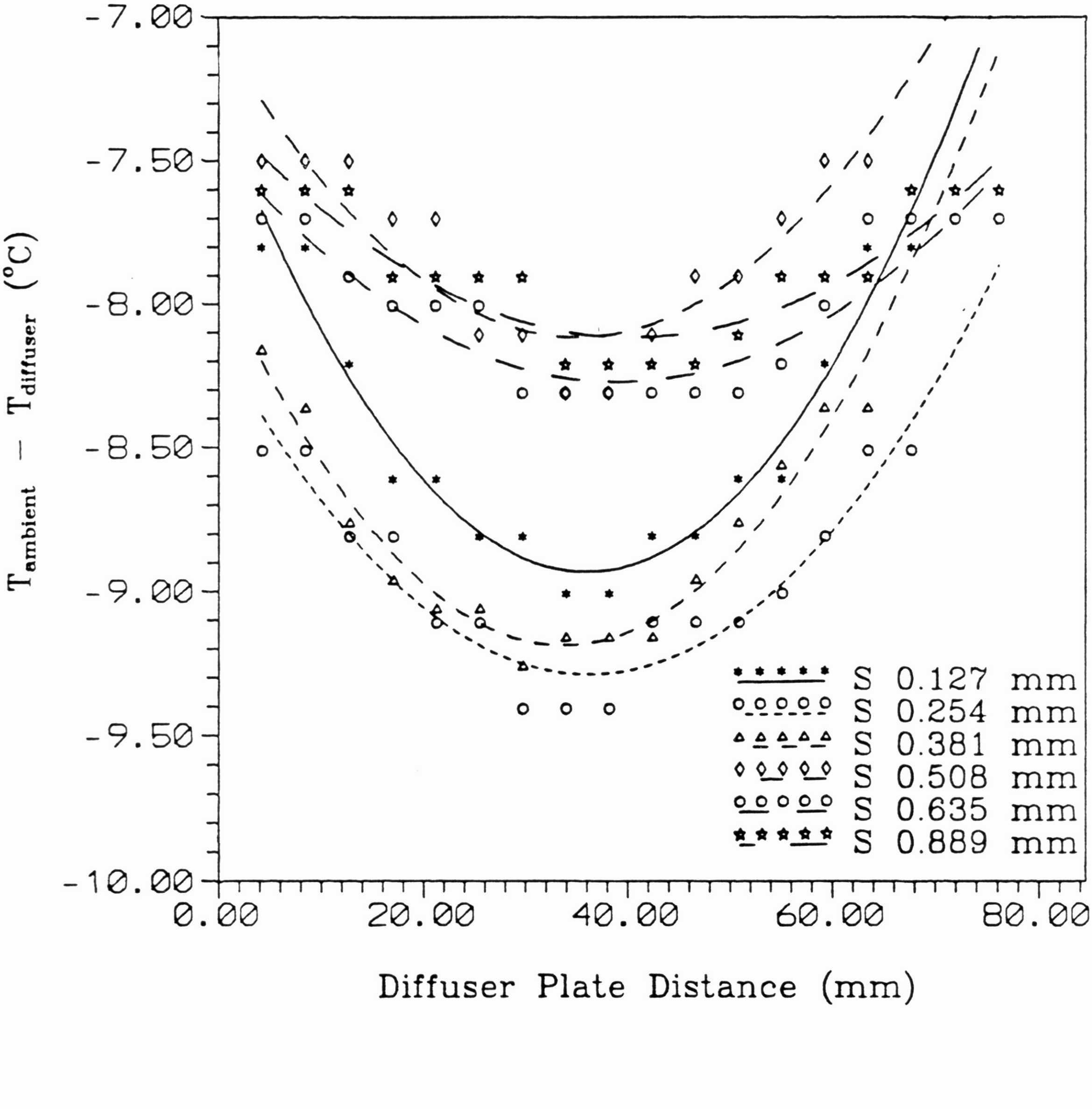


Fig. 12: Temperature Profiles at a Pressure of 5.1 kPa.

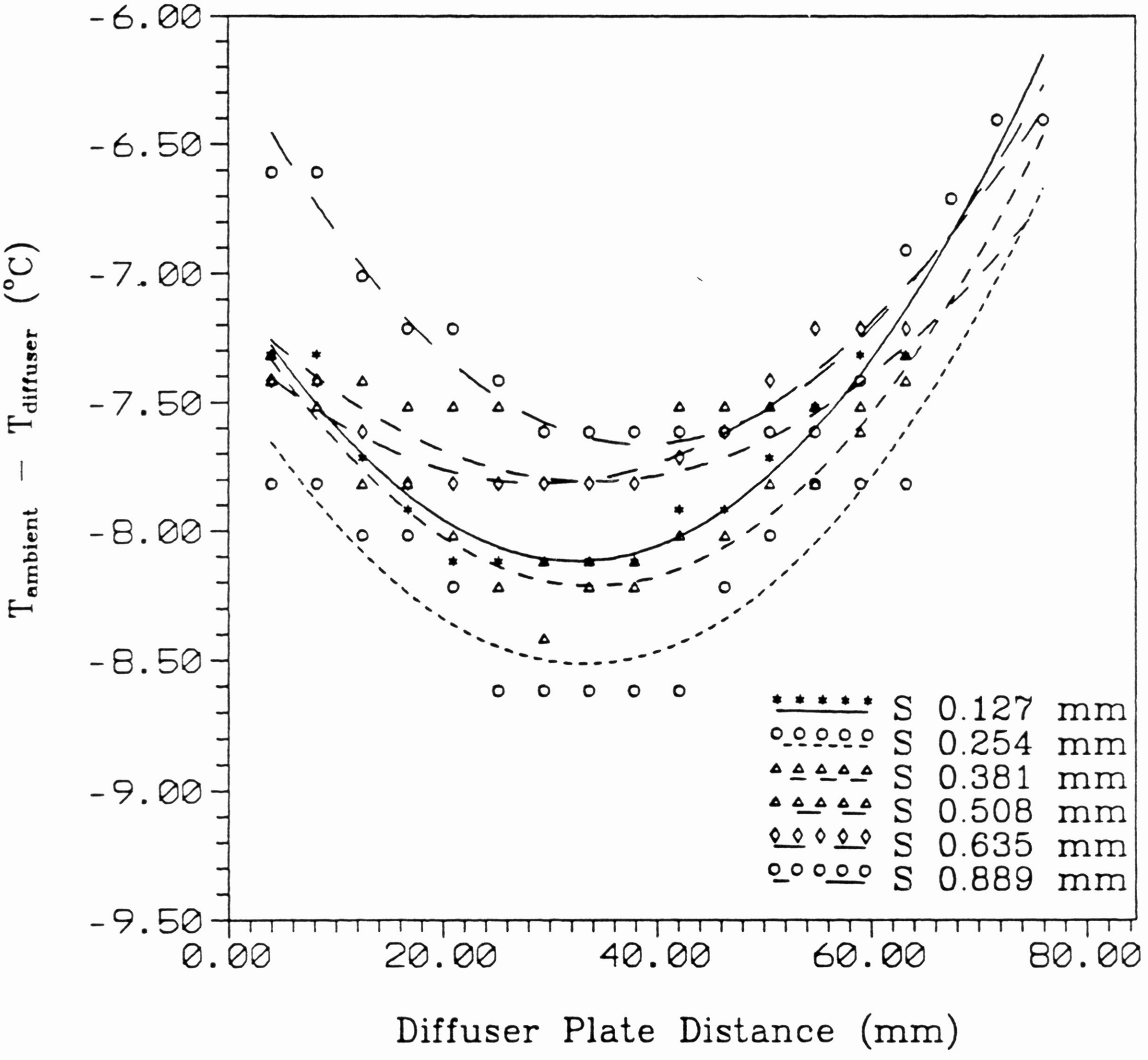


Fig. 13: Temperature Profiles at a Pressure of 4.4 kPa.

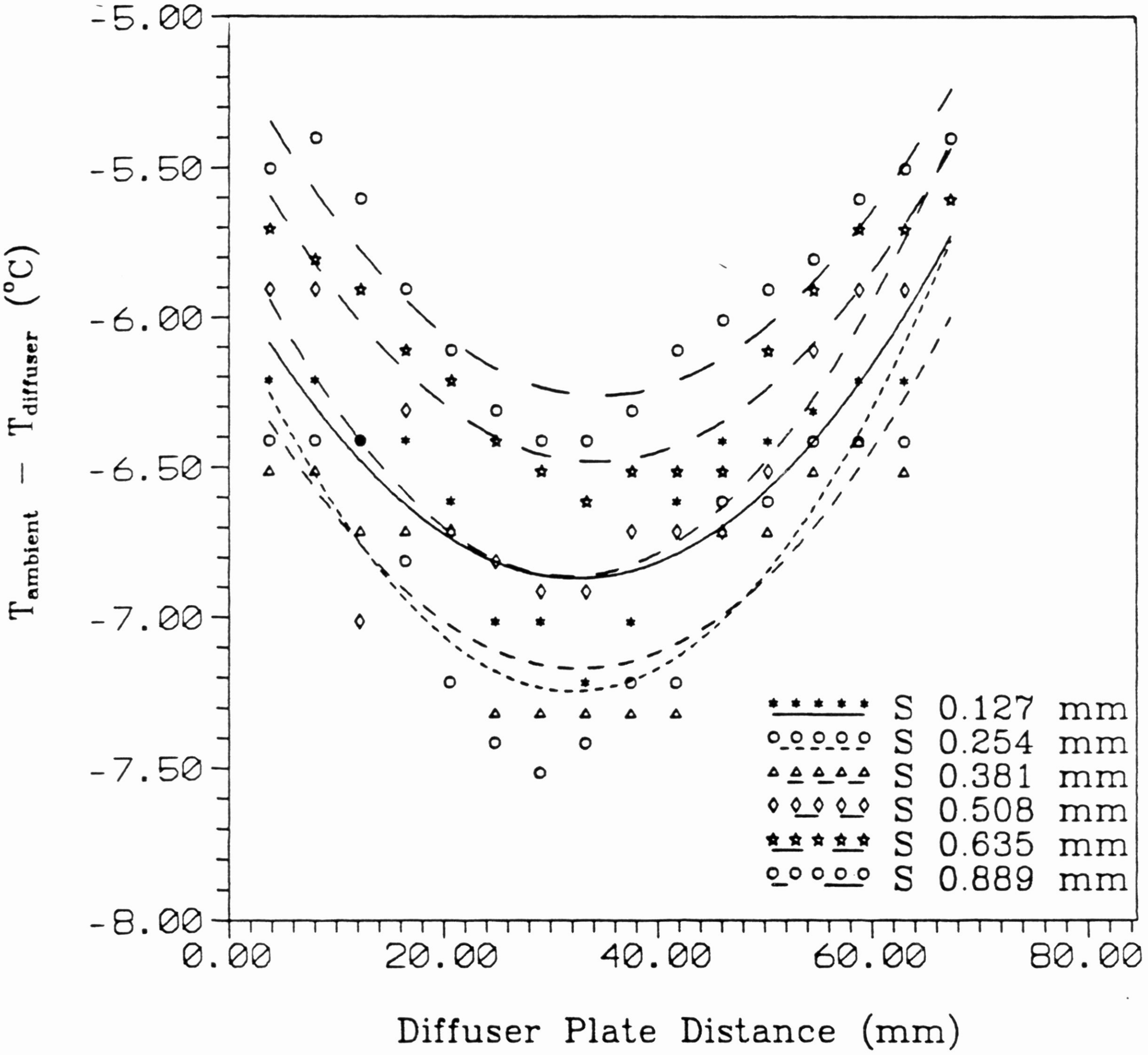


Fig. 14: Temperature Profiles at a Pressure of 3.6 kPa.

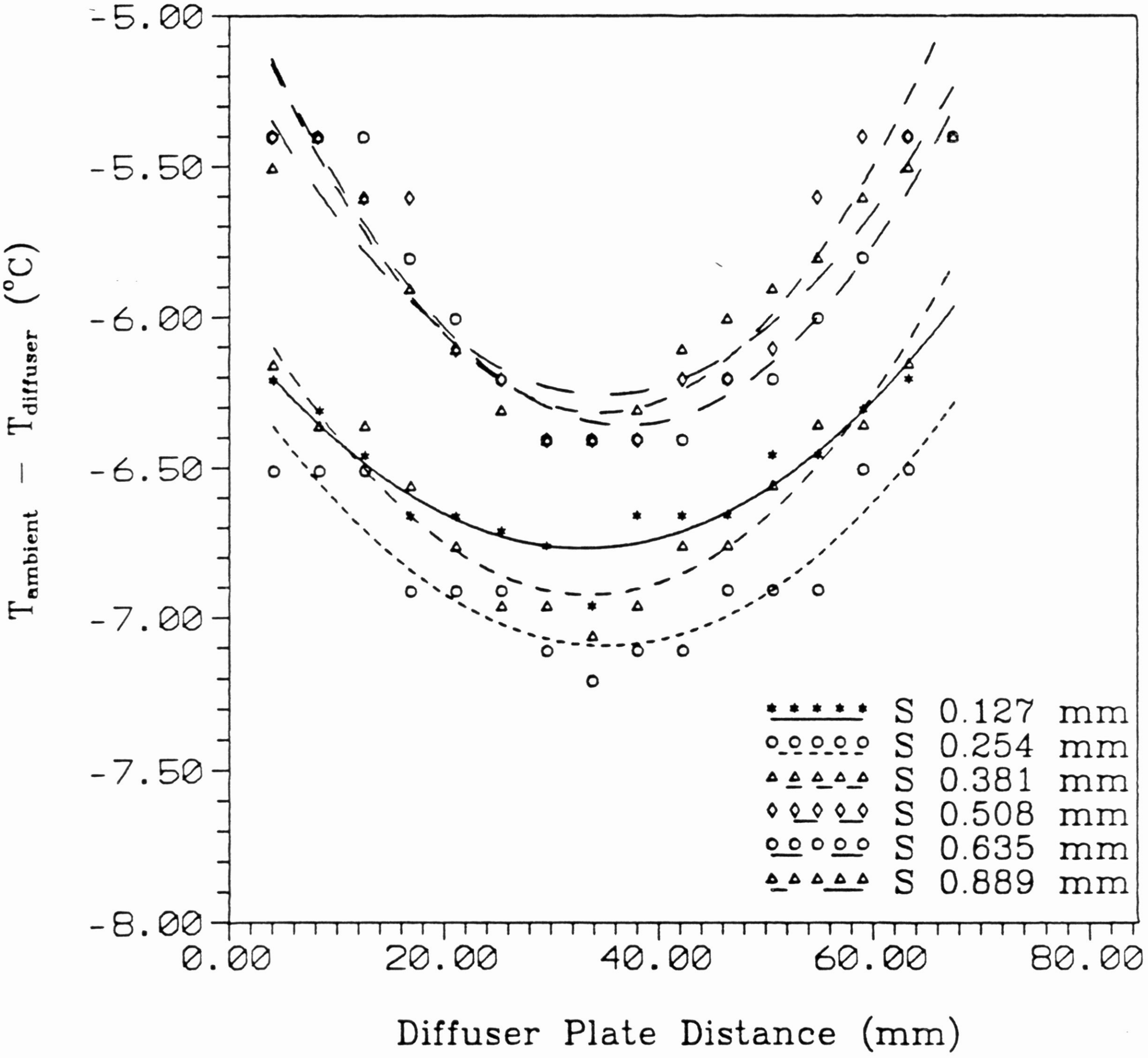


Fig. 15: Temperature Profiles at P=5.8 kPa and S=0.127 mm.

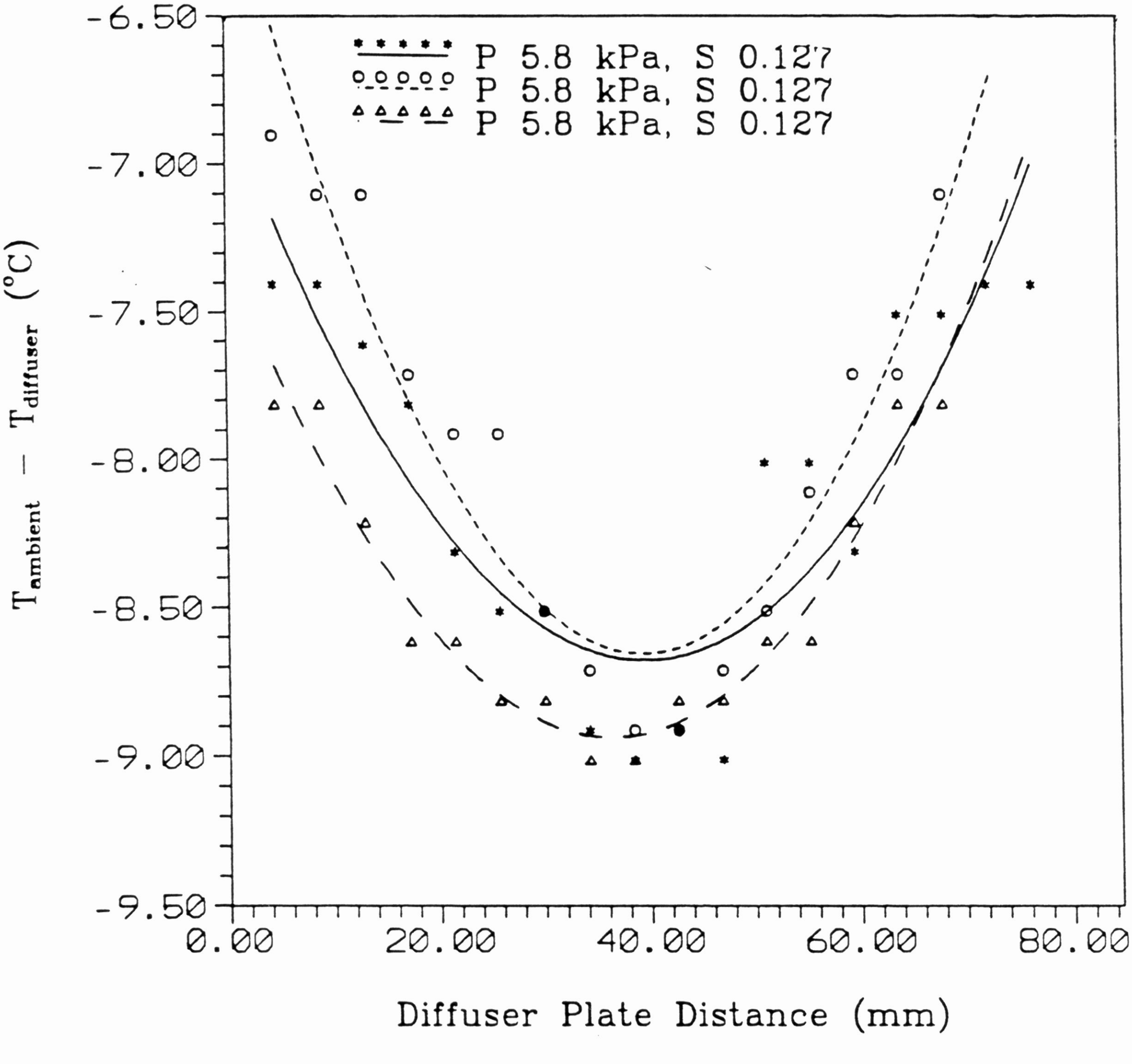


Fig. 16: Temperature Profiles at P=5.1 kPa and S=0.254 mm.

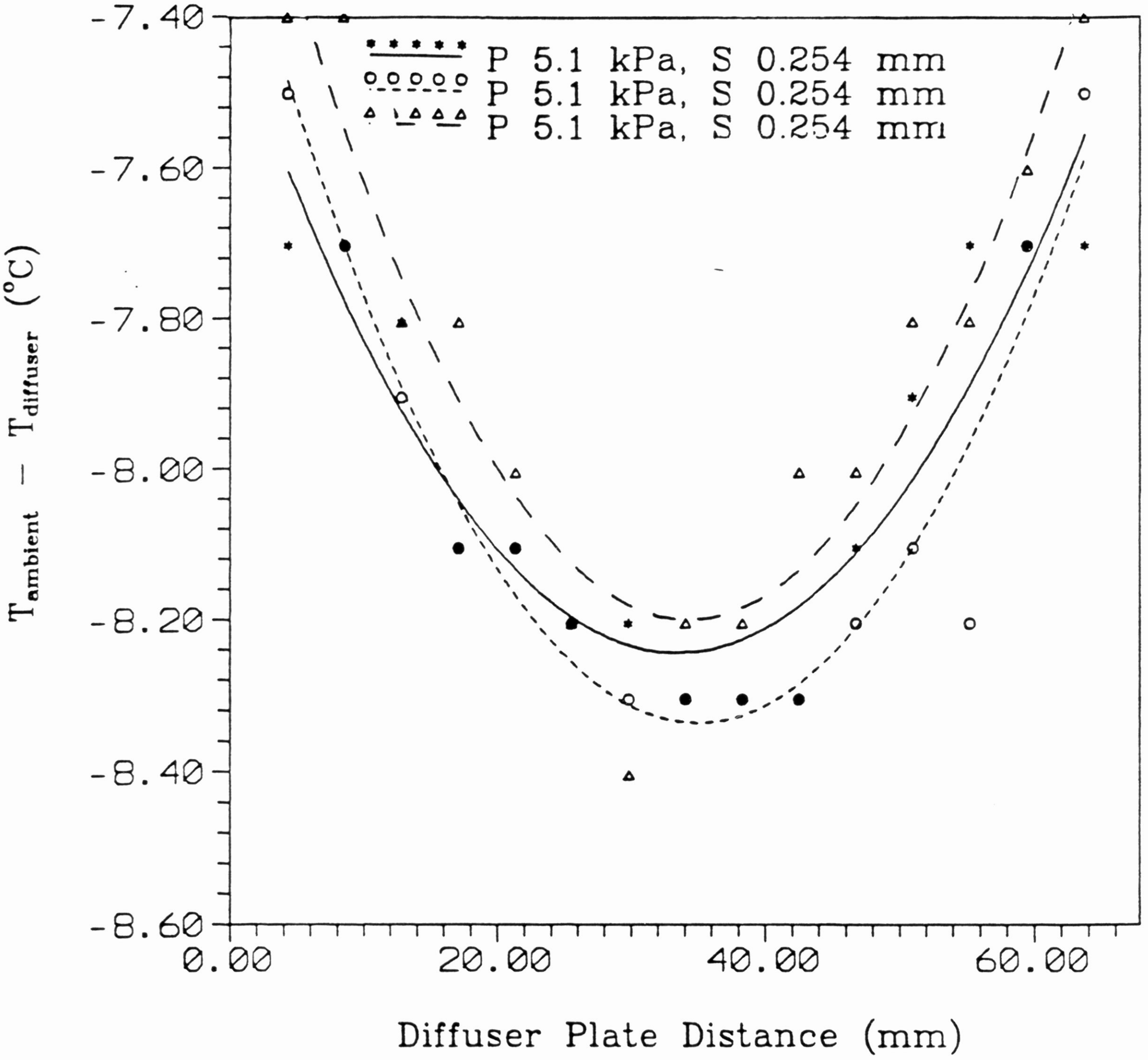


Fig. 17: Temperature Profiles at P=4.4 kPa and S=0.381 mm.

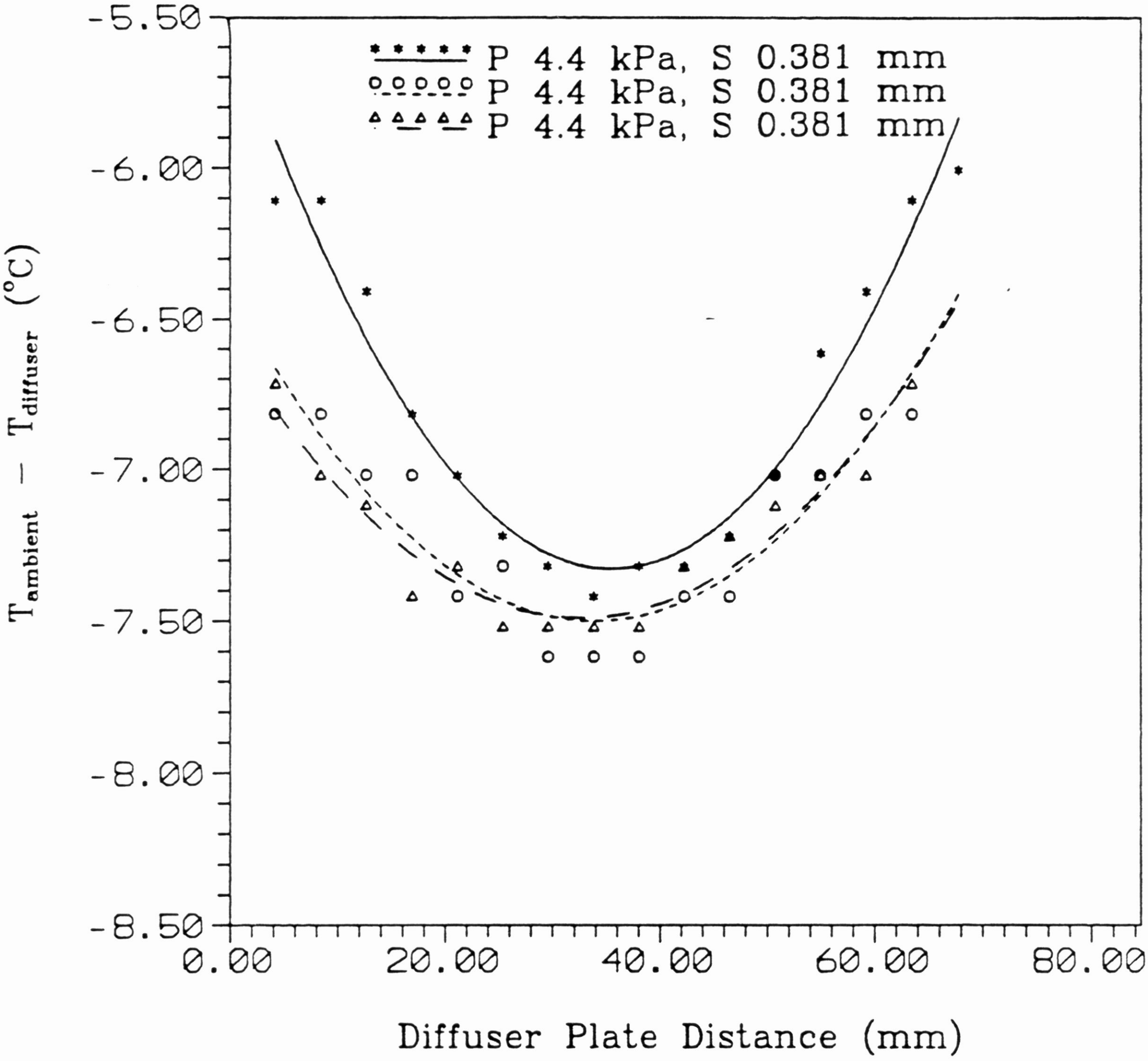
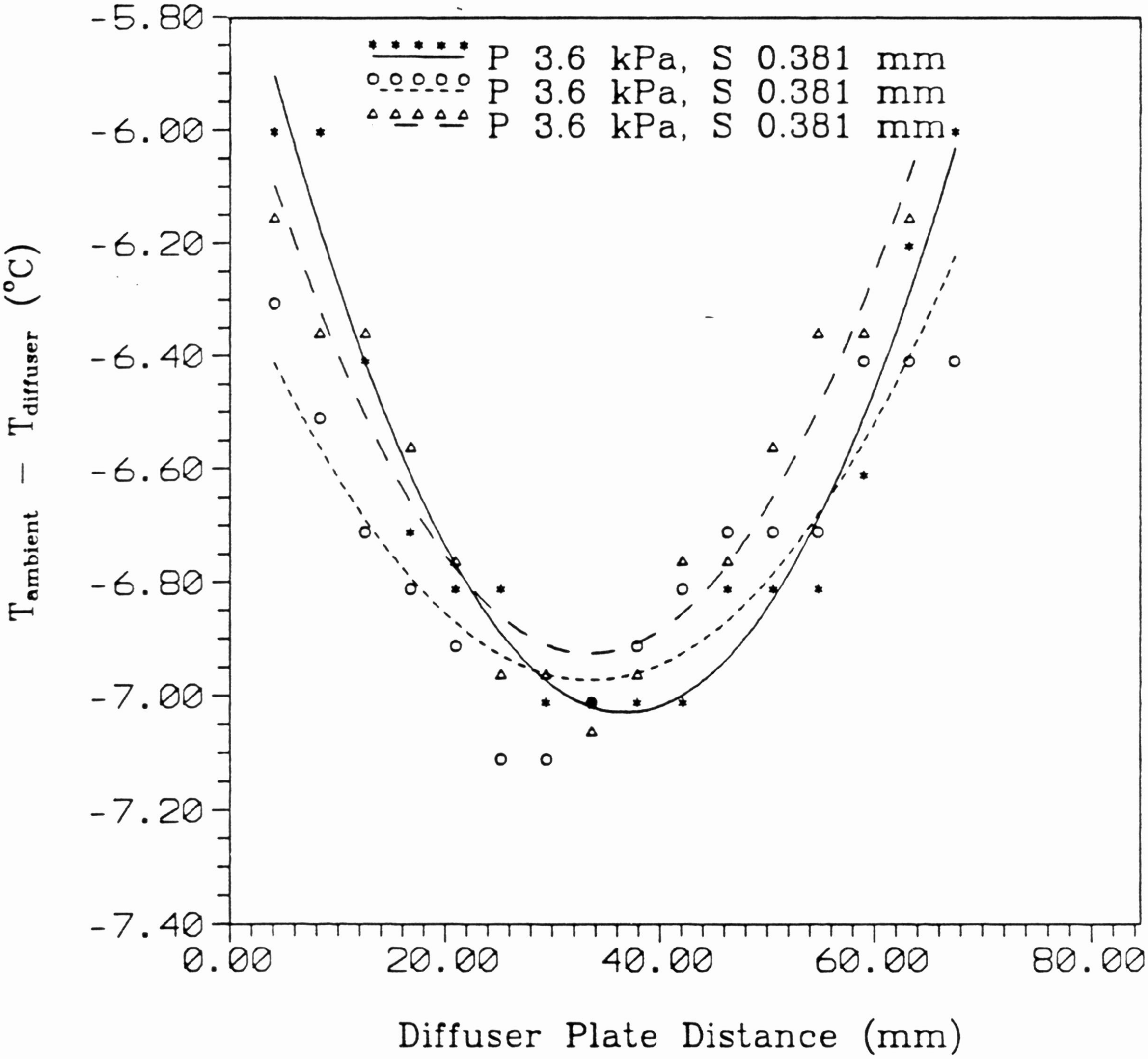


Fig. 18: Temperature Profiles at P=3.6 kPa and S=0.381 mm.



Summary and Conclusions

The following paragraph of findings summarized the results and observations stemming from this investigation. As the inlet pressure was increased to the vortex heat exchanger and the diffuser gap distance was held constant, the temperature difference between the inlet air and the bottom diffuser plate increased for all diffuser gap distances. A diffuser gap distance of 0.254 mm resulted in a larger temperature drop than all other diffuser gap distances tested. As the diffuser gap distances reached 0.508 mm or larger, the temperature profiles became very similar and at times overlapped with each other. When the temperature profiles resulting from identical input variables of inlet pressure, flowrate, and diffuser plate distance were compared, the deviation had a range of approximately 0.3°C at the center of the diffuser plate. From the experimental data taken in this research, the amount of effect the increase in inlet pressure to the vortex heat exchanger will have on the exit temperature at a constant diffuser gap distance cannot be predicted beyond the data points tested. A temperature differential exists between the center and the edge of the diffuser plate ranging from 0.5°C to 1.8°C. The temperature difference between the center and edge of the diffuser plate was possibly contributed to from a pressure differential between the plates and external heat addition from the atmosphere.

Recommendations

The following recommendations were made based on areas of uncertainty and deficiency encountered in this investigation. A wider range of pressures should be utilized in the future to observe the relationship between the inlet pressure and the resulting temperature drop. A more stable measuring device such as a depth micrometer installed at the three holes on the top plate used for measurement should be utilized in further investigation. A thinner diffuser plate should be used in further investigations to obtain a temperature value closer to the air flow temperature between the diffuser plates. The infrared camera could be attached to a computer to store all temperatures across the diffuser plate instead of using a grid and manual maneuvering and reading of the temperature on the screen. A measurement of the pressure differential between the diffuser plates would be useful for a greater understanding of the temperature profile across the diffuser plate.

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