UNIVERSITY OF CALGARY

Experimental Investigation of the Performance of an Advanced Solar Air Heater using a Porous Matrix Absorber, Outdoor Testing

by

Daniel J Nugent

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies for acceptance, a thesis entitled "Experimental Investigation of the Performance of an Advanced Solar Air Heater using a Porous Matrix Absorber, Outdoor Testing" submitted by Daniel J Nugent in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

A A Mohd

Supervisor, Dr. A. Mohamad
Department of Mechanical & Manufacturing Engineering

Ron Hugo

Dr. R. Hugo
Department of Mechanical & Manufacturing Engineering

Azaiez

Dr. J. Azaiez
Department of Chemical & Petroleum Engineering

Feb 12, 2003

Date

ABSTRACT

In much of Canada internal heating for buildings is required for over 70% of the year. Solar energy has the potential to significantly reduce the consumption of non-renewable resources used for heating, while also having a substantial economic benefit. The Canadian climate poses freezing difficulties when using liquid collectors. Using air as the working fluid has the advantage of a simpler design. Solar air heating is already established for applications such as fruit drying, crop drying, green house heating, and space heating.

Conventional solar air heaters operate with efficiencies between 40-50%. The present solar collector was experimentally tested outdoors, operating with an average efficiency of approximately 85%. The high efficiency is achieved using a porous medium to absorb solar energy and by preheating the air before entering the second pass of the collector. The collector proves that it is possible to utilize solar energy for heating buildings efficiently and economically.

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SOLAR AIR HEATING THROUGH A POROUS MEDIA ABSORBER PLATE

List of Tables

List of Figures

Nomenclature & List of Symbols

A	= *Collector surface area,* m^2
C_p	= *Heat capacity,* $kJ/kg\ ^oC$
I_o	= *Solar intensity,* W/m^2
h	= *Heat Transfer Coefficient,* $W/m^2\ ^oC$
$\overset{\circ}{m}$	= *Air mass flow rate, kg/s*
T	= *Temperature,* ^oC

Greek Letters

α	= Absorbitivity
δT	= Change in temperature
ε	= Emmisivity
η	= Efficiency
ρ	= Reflectivity
σ	= Stefan-Boltzman Constant
τ	= Transmitivity

Subscripts

1	= *Upper glass cover or upper air pass*
2	= *Lower glass cover or lower air pass*
a	= *Absorber*
amb	= *Ambient*
c	= *Glass cover*
f	= *Fluid*
g	= *Glass*
inlet	= *Incoming air stream to collector*
outlet	= *Outlet air stream from collector*
p	= *Absorber porous matrix*
r	= *Radiation*

CHAPTER ONE: INTRODUCTION

1.1 Solar Heating

1.1.1 Need for Solar Air Heating

In much of Canada internal heating for homes and buildings is required for over 70% of the year. Enormous amounts of valuable nonrenewable resources are consumed in order to provide such heating. These nonrenewable resources require expensive processing, exploitation of our environment, high cost to individual homeowners, as well as producing air pollution such as NO_x, SO_x, CO_x, and particulate emissions. International agreements are continually requiring lower emission levels of pollutants. Rising fuel prices have also created economic problems for businesses, homeowners, and the Canadian government.

Solar heating has been incorporated and proven effective for a variety of applications. Many European countries such as Italy, France, Germany, Turkey, and Greece utilize solar energy for water heating. However, the Canadian climate poses many problems regarding freezing when using liquid collectors. Therefore, increased complexity and cost of the liquid systems result from the need for antifreeze solutions and heat exchangers in cold climates.

Using air as the working fluid has the advantage of a simpler design and manufacturing process. As well, there are many niche markets where the direct use of large quantities of hot air is required. Solar air heating has already proven its effectiveness in applications for crop drying, fruit drying, and space heating (Hachemi 1998). Therefore, solar air heating is a natural choice to reduce complexity and increase economic competitiveness of solar heating systems in cold climates and niche markets.

1.1.2 Availability of Solar Energy

The sun is the source of virtually all the energy for our planet; directly or indirectly. All plant life, and therefore fossil fuel, derives its existence from solar energy. Solar energy could directly provide all the necessary energy requirements for human existence. At 5800 K, the sun radiates 1.35 kW/m^2 of power to the outskirts of our atmosphere. An interesting point to address is that assuming an earthly population of 10 billion people would require a conservative 10 kW each, and solar energy could be converted to useful power with only a 10% efficient conversion. And, if solar radiation could be collected from only 1% of the earth's surface, the human population's power supply could be entirely supplied directly by the sun (Goswami et al., 2000). Solar energy is a resource with great potential. **Figure 1.1** depicts the enormous quantity of solar energy the earth annually receives, in comparison with other sources of energy.

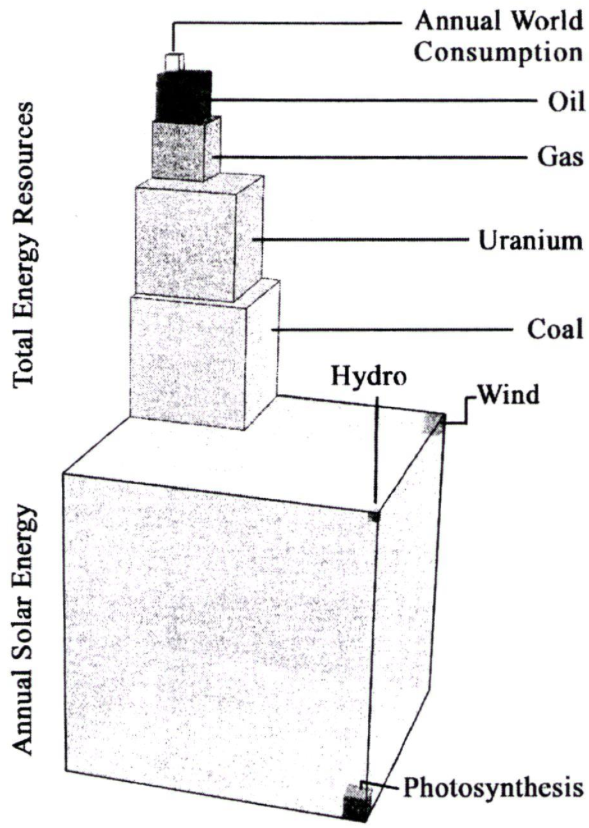


Figure 1.1 Comparison of Earthly Energy Resources (Lomborg 2001)

Solar energy is an immense renewable resource that blankets every surface of the earth. With respect to heating, individual household roofs provide a significant availability of solar thermal energy capable of providing household heating. Solar energy can be harnessed directly for this heating purpose. The sun's energy is not continuously present during a day; however, the vast amount of excess heat collected during the sunlight hours could be stored in the house using a heat storage facility. Heat stored during the day could then be accessed during the nighttime hours.

1.1.3 Practical Limitations

Although the sun does have the potential to supply enormous quantities of energy, a more realistic analysis of solar potential should be considered. As discussed in the previous section, 1% of the earth surface could provide ample energy for the earth, however, it should be considered that 71% of the earth is covered by water. One percent of the earth's surface is an enormous area, approximately 5.1 million km^2. It should be further noted that the areas where the greatest concentrations of the sun's flux fall are in remote locations; the Red Sea and the deserts of Africa.

Solar radiation available to the earth's surface is also much less than the radiation available outside of the earth's atmosphere. Approximately 25-50% of the solar radiation outside of the earth's outer atmosphere is lost upon entering the atmosphere. The greenhouse gases and water vapor reflect and absorb much of the energy radiated to the earth. Even on cloud free days as much as 30% of the radiation can be lost to the atmosphere (Goswami et al., 2000). Daily variations, seasonal variations, and pollution affect the quantity of radiation that reaches the earth's surface.

The storage of thermal energy also presents many practical limitations. In order to provide an effective continuous source of power, thermal storage must be able to compensate for variations of solar flux. Solar storage presents the need for many different forms of thermal sinks, as many different types of collectors are used. As with all energy resources, each has its own drawbacks and challenges. Future work has potential to greatly reduce the present limitations. The benefits of using solar energy for heating will now be discussed.

1.1.4 Benefits of Solar Air Heating

The most popular and obvious benefit of using solar energy for heating is the reduction in emissions that are produced by the alternative, fossil fuel burning. Solar collection doesn't produce greenhouse gas emissions. It is a clean source of energy production that allows countries to diversify their heating resources and surpass international agreements regarding pollution reduction.

Solar energy is also an unlimited power source available to everyone on earth. Developed and developing countries alike can harness the continuous energy of the sun for a variety of heating purposes. Solar energy is also an excellent choice for remote locations, as no infrastructure or utility lines are required. It is a very simple form of energy. Dangers associated with fossil fuel combustion, such as flammability and explosivity, are not a factor. Solar energy systems are less sensitive to operate than combustion engines, as only a small source of electricity is needed to run a fan. This leads to a comparatively very low maintenance requirement.

Solar heating systems can also be financially competitive, before environmental damage is considered included in the fuel costs (Sharma et al. 1994). Solar energy systems such as space & water heating, heat drying and remote power sources, are the most popular systems. The utilization of solar energy is an alternative. Solar heating has the potential to eliminate the consumption of vast amounts of nonrenewable resources, thereby protecting the environment from pollutants as well as providing substantial economic benefits. In the next section a background will be given on the various forms of solar collectors available.

1.2 Background

1.2.1 Solar Thermal Energy Collectors

There are a variety of solar thermal collector types, suited to a variety of heating applications. Some collector systems provide low temperature heat for space heating purposes, while other concentrating collectors are capable of very high temperatures that are suitable for steam generation.

Concentrating solar energy collectors include collectors that use concave reflecting surfaces (**Fig 1.2 & 1.3**). The concentrating collectors reflect solar radiation and focus the energy on a specific absorption site were the working fluid is located. These collectors can attain significantly higher temperatures capable of steam generation.

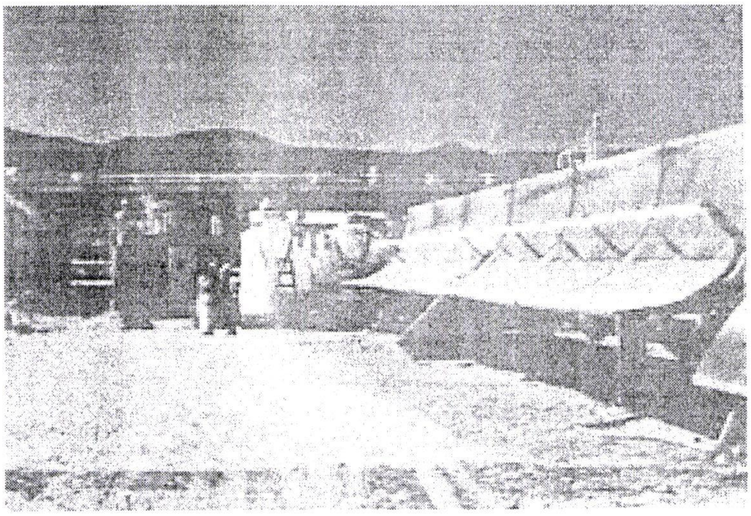


Figure 1.2 Parabolic Trough Solar Concentrating Collector (Goswami et al., 2000)

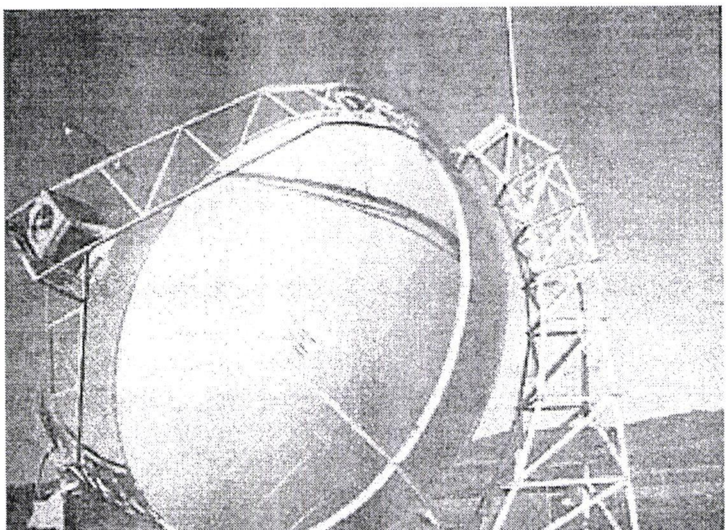
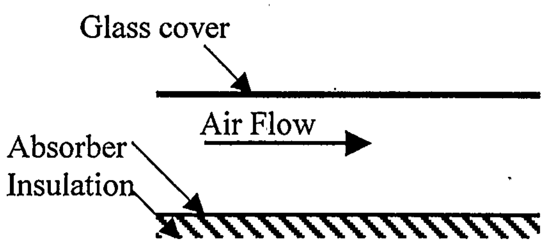


Figure 1.3 Compound Curvature Concentrating Solar Collector (Goswami et al., 2000)

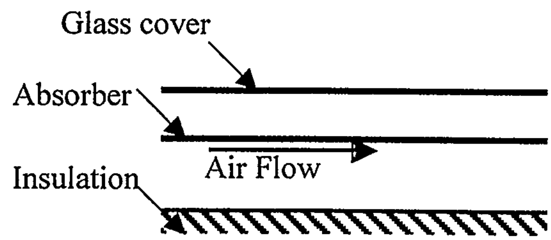
However, concentrating collectors are more complex in nature as it becomes essential to maintain a normal angle of the collector to the sun throughout the day. Therefore, sun-tracking devices are needed to track and tilt the collector throughout the day, to maintain a normal angle to the sun. These collectors result in much higher capital costs and therefore the more common method for collecting solar thermal energy is a non-concentrating collector such as the flat plate collector.

1.2.2 Flat Plate Solar Thermal Collectors

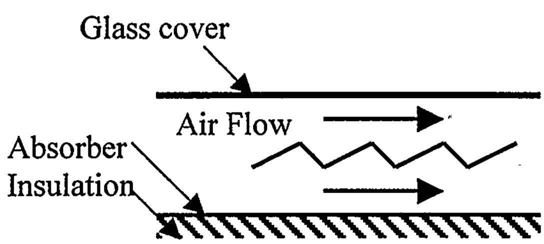
Non-concentrating collectors simply absorb solar energy by using their available surface area to capture the sun's radiation. Flat plate collectors are the most simple and common types of thermal collectors. They are composed of a large flat plate with a heat absorbent material embedded in the plate or on the plate. They usually have a glass-glazing cover to allow solar radiation to enter into the collector, but block reradiated thermal radiation from escaping. **Figure 1.4** shows sketches of common forms of flat plate solar thermal collectors.



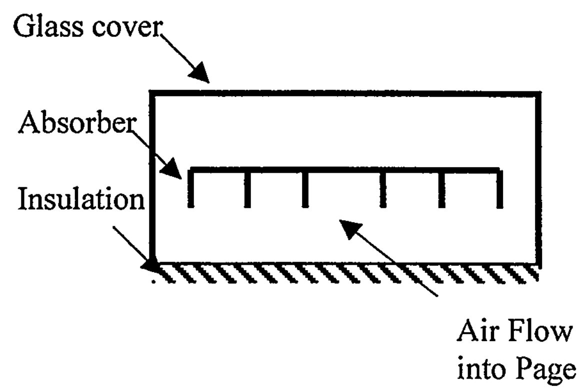
A. Conventional Collector, with air flowing over absorber



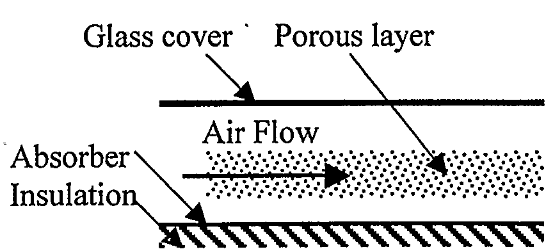
B. Conventional Collector, with air flowing under absorber



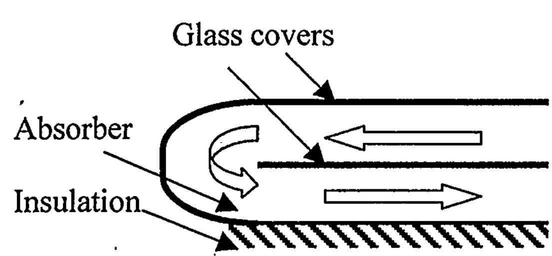
C. Ribbed Absorber Collector



D. Finned Absorber Collector



E. Porous Matrix Absorber Collector



F. Double Air Pass Collector

Figure 1.4 Various Flat Plate Solar Air Heating Collectors

Flat plate collectors have an absorber plate (usually painted flat-black in color, to maximize the absorption), which absorbs the solar radiation and then transfers the heat to a fluid. The working fluid, either air or a liquid mixture, flows through the plate or over the plate, thereby collecting the heat absorbed by the plate via convection. Typical flat plate collectors can obtain outlet fluid temperatures of around 70 ^{o}C. The thermal efficiency of these collectors depends on the working fluid, but simple flat plate solar collectors can have efficiencies on the order of about 60% for water heaters, and about 40% for air heaters under normal operating conditions (Goswami et al., 2000).

Flat plate collectors are commonly used to heat both air and water. However, due to environmental constraints in many regions, such as freezing, liquid solar collectors require many modifications such as antifreeze solutions and heat exchangers in order to enable year round use. Solar air heating offers many advantages that simplify the incorporation of a solar heater to a space heating application. The objectives of the current study with respect to solar air heating will be presented in the following section.

1.3 Objective

Solar air heating with flat plate collectors has already proven viable for many different space heating needs: agricultural crop drying, greenhouse heating, food drying, and some building space heating applications (Hasatani et al., 1985, Grupp et al., 1995). Solar air heating uses simple and inexpensive collection devises to provide direct heat to a variety of space heating applications.

By capturing the solar energy provided to the earth's surface, heating for a home may be accomplished in an economical and environmentally-friendly manner. The proposed solar air-heating device provides direct space heating. A conventional solar air-heating collector has a low thermal efficiency (approx. 40%), whereas the preliminary calculated efficiency of the proposed solar air heater is more than 80% (Mohamad 1997). The high efficiency is achieved by using a porous medium to absorb the solar energy and by preheating the air before entering the second pass of the collector. This type of collector is also superior to the conventional liquid heater on an efficiency basis (Goswami et al. 2000). The proposed collector eliminates most drawbacks of a liquid heater, such as freezing, leakage of the liquid, and high conductive losses; the proposed air heater also has a higher efficiency.

Theoretical analysis of a similar collector has been published by Mohamad (1997), which identified the collector as having potential for space heating. The main objectives of the present project were to perform outdoor experiments on the mentioned advanced solar air heater, and carry out a feasibility study of the solar space heater for a typical home installation. The output parameters and capabilities of the collector were explored and documented, with the intent of determining usefulness. The project demonstrates the scientific, environmental, and economic validity of solar air heating.

The objectives are specifically:

- To construct the mentioned advanced solar air heating collector
- Perform outdoor testing over an extended period of time
- Perform an analysis of the data collected by continuous operation of the collector
- Assess the thermal efficiency of the collector and feasibility of the collector for the Canadian environment

In order to provide an understanding of the work already contributed to solar air heating, and further understand the modifications and contributions the present collector makes to solar air heating, a discussion of solar air heating technology will be presented in the following chapter.

CHAPTER TWO: LITERATURE REVIEW

Solar air heaters have been well established as a viable and economic means of low temperature air heating (Sharma 1994). Solar air heating has been well researched for over fifty years (Grupp 1995). Though the collector's appearance is very similar to the original designs, many improvements have been made regarding the performance of the collectors. As mentioned in the introduction (Chapter 1), the concept of solar air collectors is very simple. The sun's rays heat an absorber plate, and air is then drawn across the plate to heat the air. Solar air heating research has almost exclusively focused on advances aimed at improving the heat transfer mechanism between the hot absorber plate and the air stream. Other research efforts have been interested in different types of glazing covers, and collectors without glazing covers (Njomo 2000, Ho et al., 1997).

Reviews have shown typical conventional style solar air heaters to have efficiencies between 40-50% (Ekechukwu and Norton, 1999). This leaves much room for advancements to be made to the conventional collector. Both numerical models and experimental investigations have been undertaken in order to provide advancements to solar air heating. Many mathematical models have been developed to test and evaluate various alterations made to the conventional collector (Rodono et al., 1998, Mohamad 1997). Heat transfer through the various absorber plate configurations can be very difficult to accurately model. Therefore, experimental work is required to continue or to verify the results obtained by the mathematical models.

The following section will discuss many of the significant research contributions to solar air heating collectors. Firstly, the research involving the conventional simple solar air heating flat plate collectors will be presented, followed by the numerous modifications that have been investigated in order to improve the heat transfer between the absorber and air flow. Within these categories, the contributions from the mathematical modeling research will be discussed first, followed by the more common, experimental research activity.

2.1 Conventional Bare-Plate Solar Air Heaters

Conventional collectors are comprised of a rectangular box with a glazing layer (typically glass) cover, leaving a narrow air gap (order of 10 cm) between the glass and the base of the box, which is the absorber plate (**Fig. 1.4a**). Generally a smooth surface for the absorber plate comprises a conventional collector. The collector would be positioned on a roof or south-facing wall. As an aside, having a solar collector on a wall or roof reduces heat losses from that section of the exterior envelope. Therefore, up to 87% of the wall heat losses could be regained by the solar collector (Pottler et al., 2000). The total collection of the heater would be the absorption of the solar radiation, plus heat gained from the wall heat losses.

The simplest forms of conventional solar air heaters are those that do not have a glazing layer but simply blow air under a solar heated absorber plate to collect the thermal energy. Such collectors avoid the expense of a glazing cover (usually glass) but sacrifice higher efficiencies (Ekechukwu and Norton, 1999). The Canadian company SolarWal™ has developed and marketed a similar solar air heating system using unglazed perforated metal exterior cladding as an absorber. Air is blown behind the perforated sheets to preheat ventilation air. Abbasov (1995) preformed calculations of the heat transfer from a perforated absorber, used for solar collection. These collectors are not commonly used for high temperature application (Ekechukwu and Norton, 1999).

Higher temperature collectors usually incorporate one or more glass glazing layers. Jannot et al. (1997) found that collectors that have the air flowing between the glass cover and the absorber plate have problems during a dry season. A dust layer accumulates on the absorber plate reducing its effectiveness. They recommended a more practical collector where the air flows below the absorber plate, with a glazing layer on the top **(Fig. 1.4b)**. Pottler et al. (2000) also citied that for architectural reasons flow behind the absorber plate could be more suitable for buildings that already have a glass covering for the exterior wall.

Yeh and Ting (1988), however, reported, that due to the natural convection from the absorber, a collector with air blowing over the absorber (air between the glass and absorber) had a considerable improvement in heat transfer over the collector that forced air under the absorber plate. They noted that air flowing over the absorber would lead to higher top losses, and therefore recommended a second glass cover to counter act the heat loss mechanism. For greater reduction in heat loss, two glazing layers are recommended with a double air pass to regain heat lost from the first glazing layer (Ekechukwu and Norton 1999, Mohamad 1997). These modifications create higher overall collector efficiencies.

2.2 Selective and Non-Selective Absorbers

In order to reduce the heat losses from the absorber plates of collectors, research has been done to assess the use of selective material for absorber plates. Selective absorbers are materials that drastically reduce the emittance of long wave thermal radiation, however, they significantly increase the cost of the collector. Njomo (2000) published a numerical analysis of unglazed bare plate selective collectors showing that for low wind speeds, these collectors perform comparable to conventional glass covered air heaters. For higher efficiencies under various wind conditions, a glazing layer was recommended.

Hachemi (1999) experimentally tested selective and nonselective absorbers. He experimented on a single glazed finned absorber plate system with selective and nonselective absorber plates to determine if the selective material (reducing thermal radiation heat loss) would perform better. His finding showed an insignificant increase in the efficiency and heat gain from using the more expensive selective material for the absorber. Hachemi showed that the largest problem with solar collectors is to remove the heat efficiently and quickly from the absorber plate. His recommendation was to use a well-designed fin system instead of the expensive selective absorber.

2.3 Ribbed Absorber Plates

Much work has been done in the optimization of finned and ribbed absorber plates for solar air heating, as bare-plate collectors have proven to have a low efficiency even with a glazing layer incorporated (Ekechukwu and Norton, 1999). Ribbed absorbers have been studied to determine the increase in heat transfer. Ribbed or rippled absorber plates have been designed to increase the surface area of the absorber as well as increase the turbulence across the absorber (**Fig. 1.4c**). Ho and Loveday (1997) modeled and experimentally verified incorporating corrugated building sidewall metal sheeting as a solar air heater. They placed transparent polycarbonate sheeting over the ribbed metal wall sheeting. The polycarbonate served as a glazing layer, and the metal sheeting, as the absorber plate. It was found that the thermal efficiency range was from 20-45%, however, costs for the system were very low as the absorber plate was already assumed in the cost of the building.

Bhagoria et al. (2002) experimentally studied the effects of varying the relative roughness pitch of the ribs on the absorber. Relative roughness pitch is defined as the pitch (distance between each rib beginning), divided by the height of each rib. For a constant angle of ribs, 10 degrees, results showed an increasing Nusselt number with roughness pitch from 7.57 to 12.12. The maximum heat transfer improvement compared with a smooth corridor was 2.4 times, and occurred at a relative pitch roughness of 7.57. For low Reynolds numbers, (Re <5000), the changes in relative roughness produced negligible changes in heat transfer properties. They determined the maximum heat transfer properties occurred for a rib angle of 10 degrees. Bhagoria et al. (2002) reported their results were found to be consistent with the findings of Webb et al. (1971).

Webb et al. (1971) found that the ribs produced separation of the flow, which did not reattach to the absorber for 6-8 rib heights downstream. The maximum heat transfer is known to occur at the reattachment point of the flow. For optimal heat transfer properties of the absorber plate, rib spacing should be designed to allow reattachment a maximum number of times in a given length. They concluded a very low pitch would result in no reattachment of the flow and very poor heat transfer properties (**Fig. 2.1**).

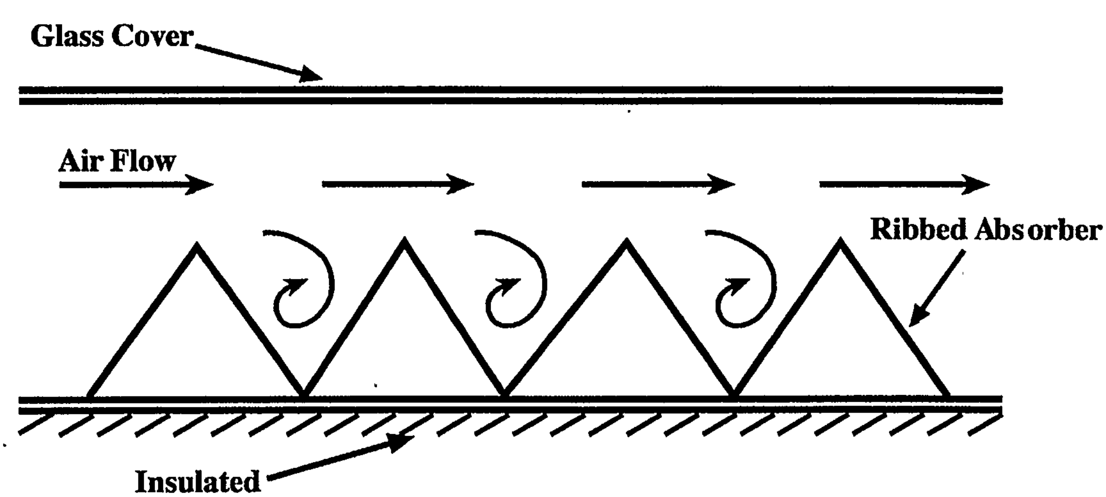


Figure 2.1 Flow Separation Through Ribbed Collectors

Others have experimented with ribbed absorber plates such as Hollands (1981), who preformed experimental work with metal v-corrugated absorber plates. He found that increases in the overall heat transfer coefficient, from a smooth flat plate absorber, were on the order of 47-300%, depending on the flow rate of the system.

Piao et al. (1994) also experimentally found that using corrugated metal sheet as an absorber plate produced a large increase in the overall heat transfer properties of the absorber plate. They used a 30 gauge galvanized sheet with 12.7 mm corrugations from valley to peak spaced at 64.7 mm apart. It was found that the corrugations increased the heat transfer coefficient by a factor of 2.8 from the conventional smooth plate absorber.

2.4 Finned Absorber Plates

Ribbed absorbers are a popular form of alteration to the conventional absorber plate; however, finned absorbers tend to have higher efficiency ratings. Finned absorbers have fin plates attached to the absorber so as to increase the surface area and thermal performance of the system (**Fig. 1.4d**). Extra manufacturing work and cost are required to form such complex plates. Much work has been done to quantify the effects and optimization of finned absorbers.

Hachemi (1994, 1995, 1999) has done a great deal of work on finned collectors. Hachemi (1994) experimentally investigated using semi circular fins mounted on the base of the absorber, situated cross flow, so as to disturb the flow and increase turbulence. He determined that to attain a 50% thermal efficiency with a conventional flat plate collector, a mass flow rate of 70 kg/ hr m^2 of air was needed, and a pumping power of 25 W was required. However, with a circular finned cross flow absorber, a 50% efficient collector could be attained at only 22.4 kg/ hr m^2, and using only one fifth of the previous electrical fan power, at 5 W.

As well, Hachemi (1995) experimentally investigated staggered parallel flow fins (**Fig. 2.2**). He used rectangular fins in staggered rows on the back of the absorber plate to increase the surface area available for convection. Hachemi determined that efficiencies of up to 75% at 50 kg/ hr m^2 could be attained with the fins.

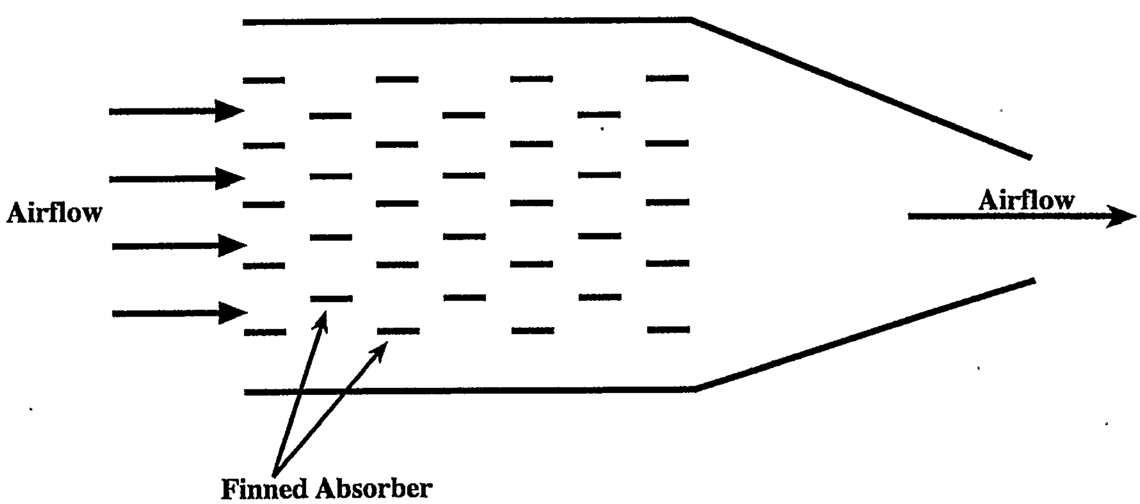


Figure 2.2 Staggered Parallel Flow Fins (top view)

Pottler et al. (2000) shows optimization for continuous fin spacing (fins running the length of collector), for varying air mass flow rates. They determined that for each mass flow rate, an optimal fin spacing could be determined. They showed theoretical modeling for optimization of continuous fin spacing, verified by two different experimental collectors. It was found that continuous fins require optimized spacing between 5-10 mm in order to provide the optimal heat transfer properties; performance better than offset fins. Offset, or staggered fins proved to have a less sensitive spacing requirement, but a higher-pressure drop for tighter spacing. However, unoptimized continuous fins proved to be poorer performing than offset fins. Optimized collectors were cited to perform up to approximately 75% thermally efficient.

As previously cited, regarding selective and nonselective materials, Hachemi has researched fins with selective absorbers. Hachemi (1999) determined the use of a selective absorber plate with rectangular staggered fins as trivial, compared with the use of a typical nonselective absorber plate with rectangular staggered fins. The use of the fins was able to produce a significant enough increase in the heat transfer coefficient to reduce the temperature of the absorber to a level where the thermal radiation lost was insignificant, thus making the use of the selective material insignificant.

As a summary, fins have been established as an effective way of increasing the heat transfer from solar collector absorber plates. On the other hand, fins pose a significant increase in the cost and difficulty of manufacturing absorber plates. The addition of fins improves the efficiency of a collector but still identifies room for greater improvements in efficiency. To provide an even greater increase in the surface area available for convection, many heat transfer applications have included the use of porous media.

2.5 Porous Material

Porous media drastically increases the surface area for heat transfer as well as increasing the mixing and turbulence of the flow, thereby also increasing the heat transfer. Due to the complex nature of heat transfer through porous media, much of the research has concentrated on experimental work, though some models have been developed. For modeling solar collection through porous media Beckman (1968) assumed for certain design criteria that the end bed temperature would be equal to the outlet temperature of the air, due to the very high increase in the thermal conductivity of the overall bed. Mohamad (1997) numerically simulated the design of an advanced collector incorporating porous media as the absorber plate. Mohamad modeled the collector and expected 75% efficiency under normal operating conditions.

The enhancement of porous media to the absorber plates of solar collectors has been investigated for many years (Beckman 1968). Various porous media have been researched and tested for use in solar collectors. Three of the most common porous media suggestions will be reviewed: glass particles, wire screens, and iron fibers.

2.5.1 Glass Particles

Due to the optical properties of glass, beds of glass particles have been studied for use as a porous absorber in solar air heaters. The hypothesis being that the solar energy will be able to penetrate in-depth through the glass media, resulting in a stratification of the thermal energy. Collier (1979) investigated crushed glass beds and determined similar thermal performance to using wire screen matrices as the porous media. Hasatani et al. (1985) used small glass beads for packing of the bed and determined an increase in efficiency of 10% over the conventional flat plate collector efficiency of 47%. However, it must be noted that adding a glass bed to the system drastically increases the weight of the collector.

2.5.2 Wire Screens

The use of wire screen matrices for porous absorber beds in collectors has also been well researched. The screens are a uniform and consistent type of porous media for packing the solar collector beds. Hamid and Beckman (1971), Prasad and Saini (1993), and Varshney et al. (1998) have preformed analytical and experimental work on screen beds.

Sharma et al. (1991) preformed outdoor experimental work on a wire screen filled collector box. They found an increase in thermal performance from 23-29% over a bare plate collector as mass flow rate increased from 0.0159 – 0.0318 kg/s m^2. They determined for varying packed bed absorbers the efficiency could increase to 61%. The tests showed increased performance results as porosity decreased from 0.953 to 0.875. They found that the improvement in thermal efficiency, over the bare plate collector, could be on the order of 60% or greater. Performance improved with increase in effective volumetric thermal capacity and surface conductance.

2.5.3 *Iron Fibers*

Another form of porous media studied for solar air heating is iron fibers. The metal fibers have a high thermal conductivity as well as a high thermal capacity compared with air, which can help stabilize minor output temperature fluctuations. Iron fibers are attained in the form of waste turnings from machine shops, or commercial steel wool.

Singh (1978) researched a packed bed solar air heater using iron turning (waste from machine shop) and determined an overall collector efficiency between 59% and 83% for temperature rises of 35 °C and 12 °C, respectively. Singh noted a drastic drop in collector efficiency as temperature rise increased to greater than 20 °C.

Yeh and Ting (1988) experimentally studied, in laboratory conditions, the effectiveness of various thermal enhancement processes. With respect to the performance of a bare plate collector, a collector with downward pointing fins (air forced under the absorber plate), produced negligible improvements in thermal efficiency under the flow conditions investigated. A collector with upward pointing fins, where the air was forced between the glass and absorber, produced a 20% improvement in thermal performance, and adding porous material (iron filings) produced up to a 75% increase in the thermal performance. At the 75% increase in performance condition, a four-fold pressure drop increase occurred (in comparison with the bare plate collector). They recommended a decrease in the amount of iron filings used, and cited their other packed bed collector which resulted in a 50% increase in heat transfer effects and only a doubling effect in the pressure drop (from the bare plate collector).

2.5.4 Pressure Drop in Porous Media

Porous media has significant advantages in increasing the heat transfer from the bed, however, it can be seen that the pressure drop must be considered. Pottler et al. (2000), references that the ventilation power requirement may be as high as 20% of thermal output for some collectors. Therefore, great effort should be made to quantify and minimize pressure drop across the collector bed.

Cheema (1979) preformed an experimental analysis of porous packed bed collectors with iron turnings and found the pressure drop to be proportional to the flow velocity, raised to the power of 2.25. A 5 cm bed packed with iron filing reported a pressure drop of 30 times that of the empty box (Singh 1978). However, Cheema found that by increasing the packed bed depth to 15 cm, while maintaining the same flow rate, only 3 times the pressure drop of the conventional box occurred. When varying the depth of the beds from 7.5-15 cm, the thermal performance was found to be similar (within 10%) between the two beds. Therefore, the decrease in velocity (therefore turbulence) in the deep bed was more than compensated for by the increase in heat transfer coefficient, and was found to perform the best. An average density of 102 kg/m^3 was used for packing each of the various beds. Pressure drop was confirmed to be in linear relationship to the collector length.

Ahmad et al. (1995) also experimentally investigated the pressure loss resulting from screen packed bed collectors. They noted that when considering the extra energy required for pumping, an optimal mass flow rate could be found to balance the increases in turbulence gained with the losses incurred from increased pressure drop.

2.6 Variable Width Collectors

Some work has also considered the sizing and dimensioning of collectors (Hegazy et al., 2000). They studied the effects of varying the width of the solar air heaters. Trapezoidal and parabolic shapes replaced the conventional rectangular shaped collector frames. Theoretical models developed showed that variable width absorbers produced very similar results to rectangular collectors. Marginal decreases in heat gain and thermal efficiencies resulted in both the trapezoidal and parabolic shaped collector. The work showed the viable use of variable shaped collectors for applications that have design constraints, such as roof installation or limited building room.

2.7 Storage

One of the problems that exist for incorporating solar collectors into buildings is the issue of heat storage for more constant heat accessibility. Often there is excess heat from a solar air heater available during the day to heat the building, but auxiliary heat is required after sunset. Many options are suggested for heat storage such as phase change materials, water, and more commonly, rock beds. Fath et al. (1994) modeled a solar air heater using phase change material filled tubes as the absorber surface. The system operated on a thermosyphon (convective natural pumping system) 24 hours a day with the material rejecting heating during the night that was stored in the phase change material during the day. The calculated efficiency over the day ranged from 27-64%. Phase change material can also be used for heat tank storage. Kuzay et al. (1971) studied using melting salt hydrates for solar heat storage.

Rock beds can also be used as a thermal sink to store solar energy collected. Rock beds have an advantage of being inexpensive and readily available, though they can be large in size. Abbud et al. (1995) have done numerical analysis regarding the options for storing heat in rock beds during the day, so heat can be accessed in the night. Their experiments included heat storage by constant temperature air extraction from a solar heater and also studied constant flow extraction from the solar collector. They define optimum storage design characteristics in order to maximize heating potential. Constant-temperature heat output from the collector showed better heat storage than constant flow for heating under 50 °C, while a constant flow showed better heat storage results for flow temperature over 60 °C. The results show a 60% solar fraction for annual heating requirements, using the rock bed storage system.

2.8 Summary

Summarizing, it has been shown that a conventional solar air-heating collector has low thermal efficiency 40-50% (Ekechukwu and Norton, 1999), where the preliminary calculated efficiency of the proposed solar air heater is more than 80% (Mohamad 1997). This high efficiency is achieved using a porous medium to absorb the solar energy and by using a double pass preheating loop for the air. This type of double passing collector has proven superior to the conventional solar air heater for thermal performance (Ekechukwu and Norton, 1999, Mohamad 1997). Research has shown porous media to be the highest thermal enhancement method to the conventional solar air-heating collector (Yeh and Ting, 1988). Data for double-pass air heating with a porous medium does not exist. Insufficient data is available for outdoor experimental testing of high efficiency solar air heaters. The purpose of this study is to combine previously proven optimal design criteria, with additional innovation, and provide a design verified by outdoor experimental testing for the highest practical thermally efficient solar air collector available.

CHAPTER THREE: Experimental Procedure

3.1 Motivation

As previously discussed in the literature review, in order to verify the effectiveness and usefulness of the present solar air heater, outdoor experimental testing must be studied. Numerical work had been presented for the collector (Mohamad 1997). In order to further the study of the advanced solar air heater, a feasibility study was undertaken. An experimental prototype of the present collector was built and tested under actual outdoor operating conditions in Calgary, AB. The collector was placed atop the U of C weather research station during the winter months. The following section will detail the apparatus used, the measurement devices and calibration process, and the experimental procedure.

3.2 Apparatus

The collector was designed and dimensioned for a practical heating system. The flat plate collector consisted of the typical rectangular collection section, as well as a triangular outlet nozzle and fan. Views of the collector and experimental setup can be seen in the **Fig.'s 3.1** and **3.2.**

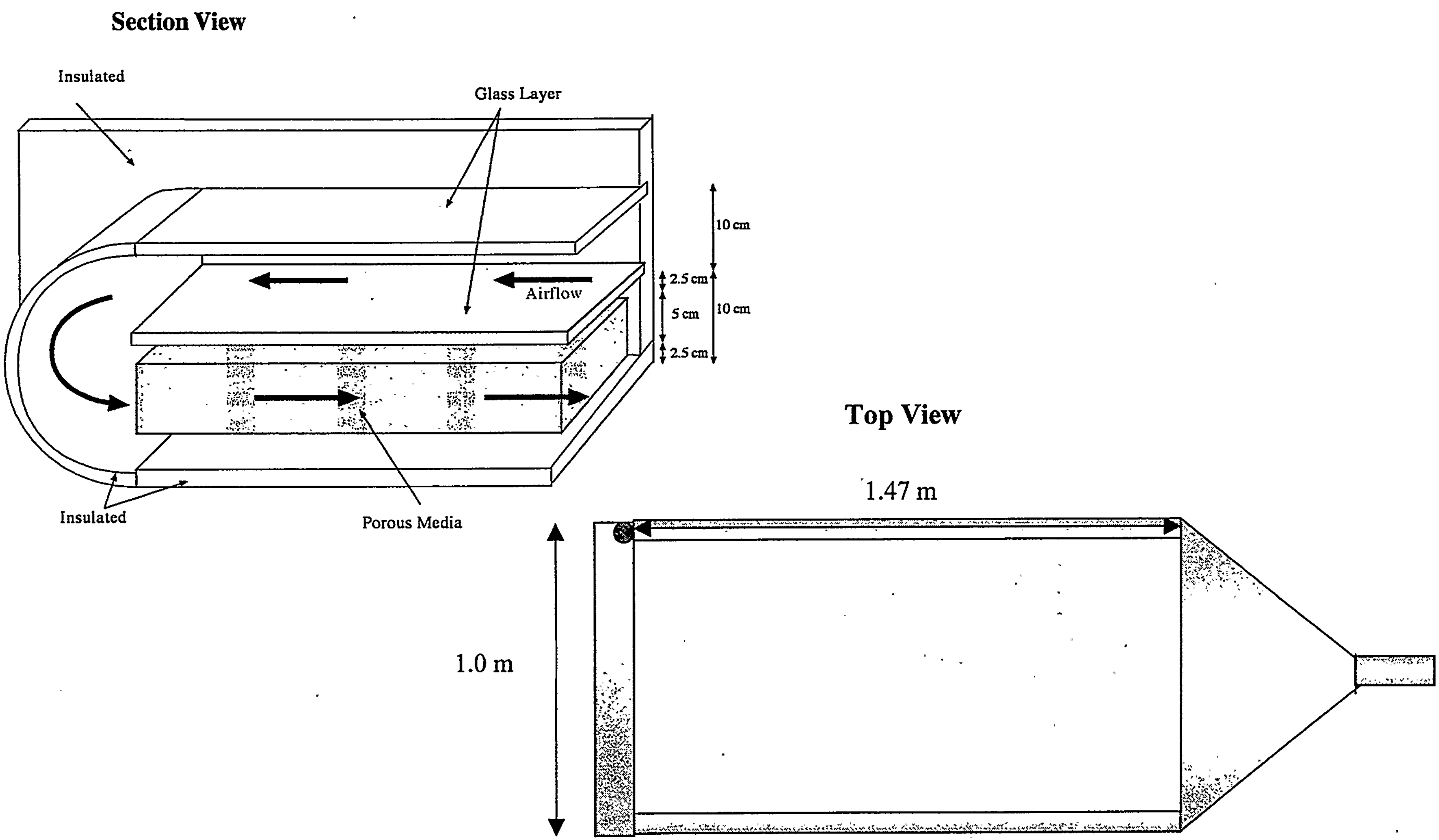


Figure 3.1 Schematic of Present Solar Air Heating Collector

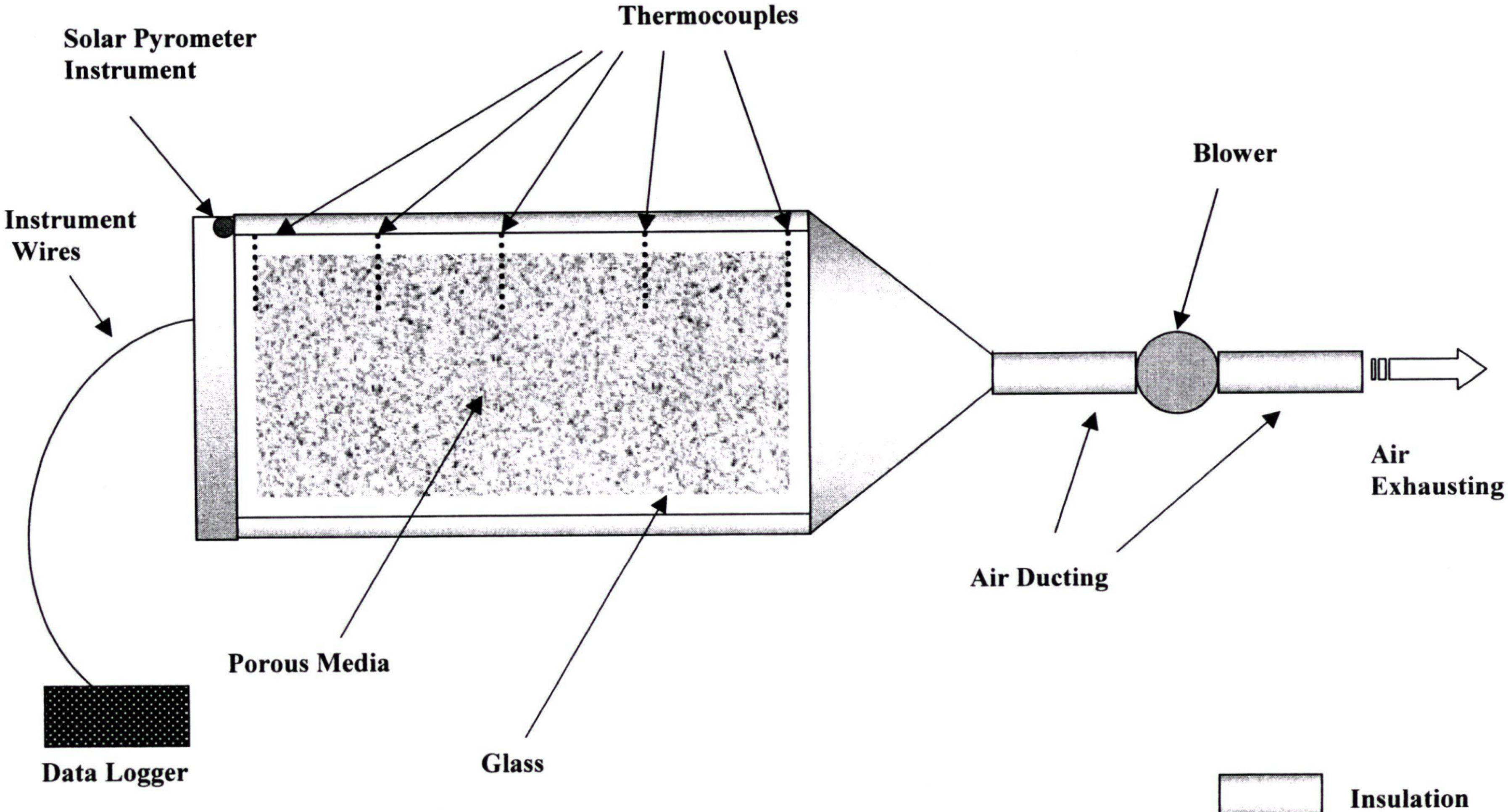


Figure 3.2 Experimental Apparatus Schematic

3.2.1 Collector

The main body of the collector box was composed of 1.59 cm (5/8") laminated plywood. The dimensions and cross sectional view are shown in **Fig. 3.1**. The collector provided a rectangular glass collection area of 0.99 m X 1.5 m. The glazing layer material was 3mm plain glass. The upper and lower glazing layers slid into 0.64 cm (¼") grooves cut into the surrounding wood box. Glass edges were siliconed and taped where required to avoid air leakage and water intake. The depth of the collector was 20 cm from the top glass layer to the bottom of the wood absorber box, with 10 cm between the glass layers. The sides of the collector were insulated with 5.1 cm (2") styrofoam building insulation in order to reduce wall heat loss from the bed. The transition from the first airflow pass (top) to second airflow pass (bottom) was accomplished by using a 20.3 cm (8") plastic irrigation pipe cut in half across the diameter. Surrounding the half-pipe was styrofoam insulation foam, used to reduce heat losses.

Similarly, the triangular nozzle section of the collector was composed of 1.59 cm (5/8") plywood, covered in the styrofoam building insulation. The end of the triangle was cut off so as to tightly fit a 10.2 cm (4") – 12.7 cm (5") tin air duct nozzle increaser. A series of air duct nozzle increaser's followed so as to facilitate the 17.8 cm (7") diameter, Irdex blower model AMU 400. The blower was capable of maintaining a constant flow rate of 400 CFM with up to a 1-inch water column of pressure drop. A short pipe followed the fan and an open box covered the pipe to reduce the effect of wind backpressure.

The triangular nozzle section was also covered with the 5.1 cm (2") styrofoam building insulation. Insulating foam was also used to seal and insulate the air duct nozzle. The air duct increasers were wrapped with multiple layers of fiberglass insulation to minimize heat loss. All surfaces (except the glazing sheets) of the collector were painted a flat black using spray paints.

3.2.2 Porous Material

The porous material was placed in a bed in the collector using a small wooden frame to hold the porous material off the bottom of the bed, thereby reducing heat losses. The 0.64 cm (¼") wood dowel frame was covered with plastic window screen to contain the porous material. The frame measured 0.05 m x 0.95 m x 1.45 m so as to keep a 2.5 cm border around the "mattress" in all directions to reduce heat loss to the walls and above glazing layer.

The porous material used in the bed was industrial fine steel wool. Steel wool rolls were expanded to increase their porosity in the bed (**Fig. 3.3**). The frame and steel wool were all painted a flat black using spray paints. A total of 626 grams of steel wool were evenly dispersed in the bed. Therefore, the porosity of the bed was calculated to be approximately 99%.

$$Porosity = \frac{V_t - V_{steel}}{V_t} x100$$

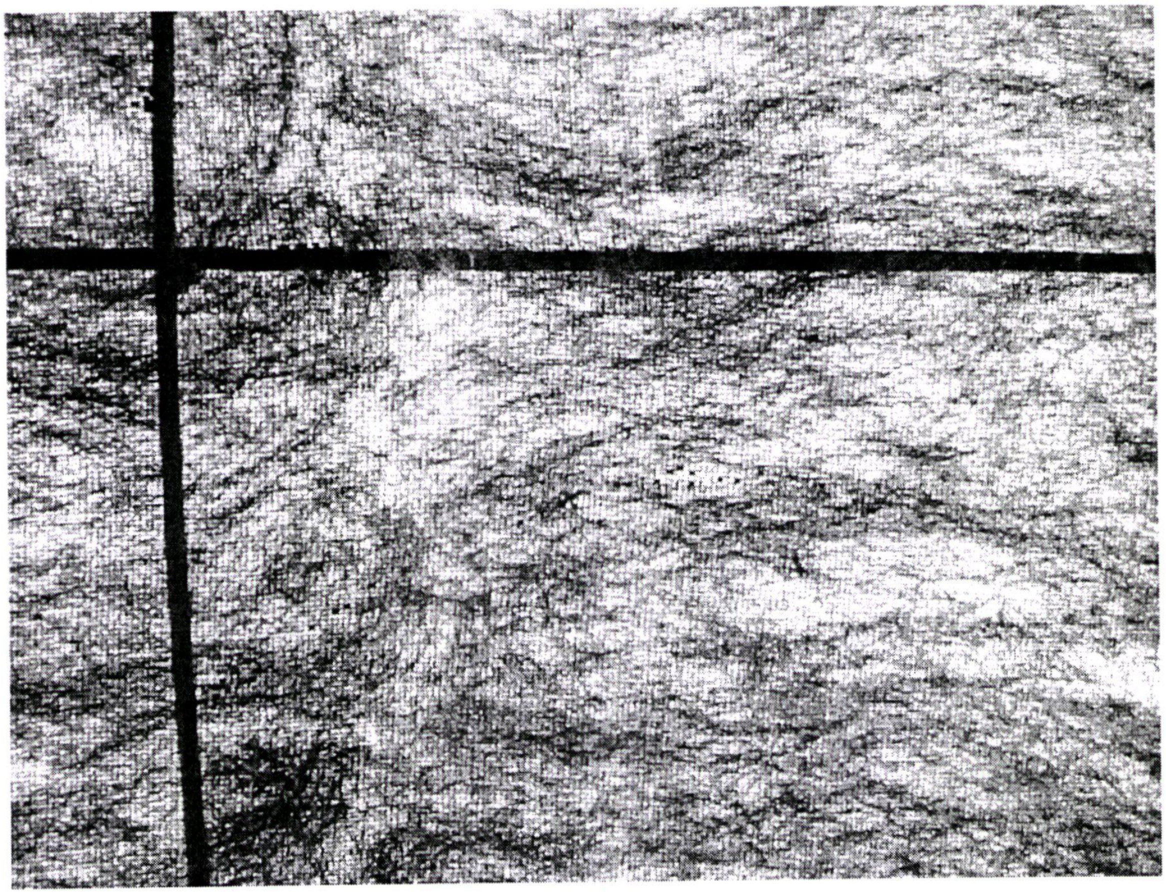


Figure 3.3 Photograph of Collector's Porous Matrix Absorber

3.3 Measurement Devices

3.3.1 Temperature

Seven copper constantan type J thermocouples were used in the collector. Five thermocouples were spaced 20 cm apart down the length of the collector, protruding at a depth of approximately 30 cm into the porous bed. The remaining 2 thermocouples were placed protruding 5.1 cm (2") and 7.6 cm (3") respectively, in the centerline of the 10.2 cm (4") outlet air duct.

3.3.2 Solar Intensity

The solar intensity was measured using a small pyrometer made by LI COR, model pyranometer, PY21175, which was fixed into the upper corner of the insulating styrofoam attached to the collector, parallel to the face of the collector. Therefore, the reading of the pyrometer was that actual solar intensity incident on the face of the collector.

3.3.3 Flow

The flow rate was measured using an orifice meter built to the specifications of the ISO standard for orifice meters. The orifice meter was installed 25 diameters down stream of the collector outlet. The diameter of the pipe used for the meter was 12.7 cm (5") with the β value being 0.78. The added pressure drop on the system, from the addition of the orifice plate, was measured before and after installing the orifice meter. A negligible difference in pressure drop was obtained after the removal of a contracting nozzle on the outlet of the fan and the addition of the orifice plate was installed. (A contracting nozzle in the original system was not required in the orifice system and was removed in order to decrease the pressure drop and maintain the original pressure drop of the system. Therefore, ensuring the same fan volumetric flow rate through the system after the installation of the orifice meter.) As mentioned, the fan specifications did allow for consistent flow rate operation for up to a one inch of water pressure drop across the fan (the contracting nozzle was removed as a conservative measure to ensure pressure drop never exceeded one inch of water). An Omega PX277 pressure transducer was used to record the pressure differential and the voltage output was read on a multimeter.

The flow rate (of the original system before the orifice meter was installed) was also measured using a digital hotwire anemometer probe by Airflow Developments Ltd. model TA2-3K. A four section radial grid was composed to help record the average velocity across the 10.2 cm (4") air duct. The velocity profile confirmed turbulent flow and consistent readings across the face were obtained. The average flow rate through each radial section was found and the total flow rate was found by integrating the flow over the respective area of the pipe face.

The hot wire anemometer test was performed early in the morning with cloud cover when the temperature rise in the collector outlet air stream was small (negligible). The hotwire anemometer results were consistent with the orifice meter measurement.

3.4 Calibration of Instruments

3.4.1 Temperature

The seven copper constantan type J thermocouples were calibrated in an ice bath to 0.1 °C. The ice bath temperature was confirmed using a calibrated mercury thermometer. The accuracy of the thermocouple readings were also verified once installed in the collector outdoors by comparison with the local weather research station data, which measured ambient air temperature approximately 30 meters away. In the nighttime, under no solar insolation, the thermocouple readings could be compared with the weather station data throughout the duration of the testing.

3.4.2 Solar Intensity

The solar intensity reading was obtained from the pyrometer, which was calibrated onsite by comparison to the solar intensity readings of the U of C weather research station. The weather station obtains calibrated solar intensity readings from an elevated rooftop across campus (approximately 1 km away). The weather station measures solar intensity perpendicular to the horizontal. Therefore, the experimental pyrometer was positioned horizontally on the weather station roof so as to measure the solar intensity incident on the horizontal. Data was collected over a period of 2 days and a consistent linear correlation was found in measurements before noon (of the particular days) after which cloud cover began causing variations between the two stations. **Figure 3.4** shows the correlation of the experiment's pyrometer to the U of C's weather station pyrometer data. It can be seen that a consistent sensitivity factor was found for an extended period of hours. The linear sensitivity factor for the calibration of the pyrometer was found to –117 W/m^2 / mV.

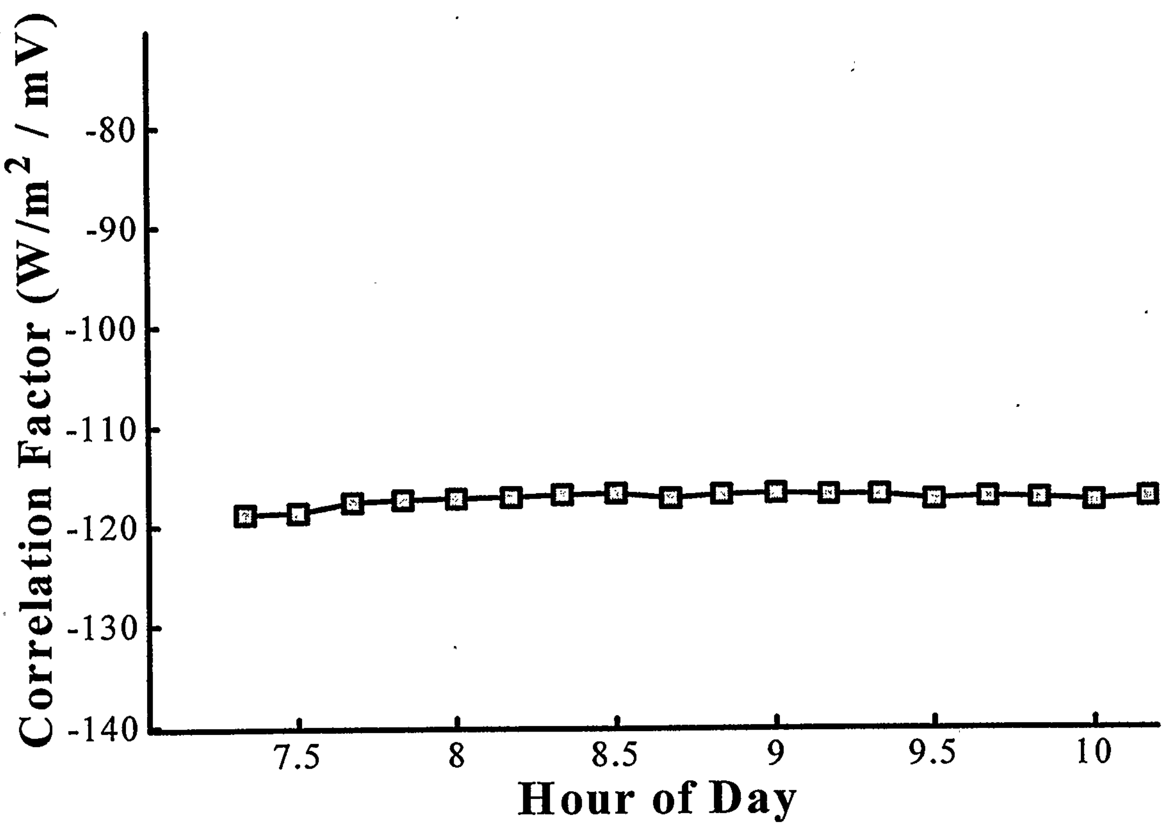


Figure 3.4 Pyrometer Calibration Graph

3.4.3 Flow

The flow measurement was obtained using an orifice meter and verified by a hot wire anemometer. The orifice meter was built to the specifications of the ISO and therefore, calibration was previously ensured regarding the accuracy of manufacturing to the ISO standards. Flow rate was determined from the pertinent pressure drop equations. The pressure drop measurement was obtained using an electronic pressure transducer. The pressure transducer was previously calibrated in a laminar flow wind tunnel by a colleague, and known to be accurate.

The hot wire probe was used as a verification of the orifice meter reading. The probe was calibrated in a wind tunnel in the university basement. Various readings from the hot wire anemometer were compared to the corresponding readings given by the wind tunnel manometer. The corresponding graphical relation allowed an accurate output from the hotwire to be determined **(Fig. 3.5)**.

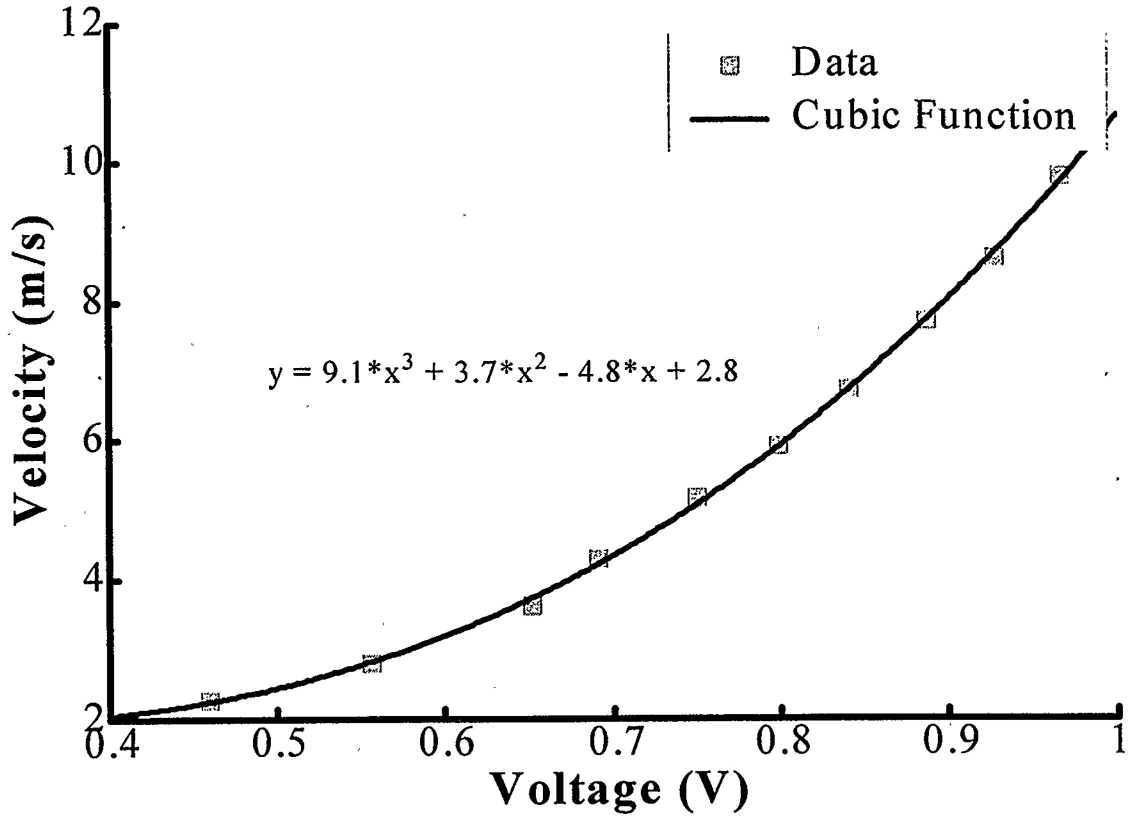


Figure 3.5 Calibration of Hot Wire Anemometer

3.5 Data Logging

3.5.1 Temperature

A Campbell Scientific Inc, 21X Micrologger, data logger was used to record and log output values from the thermocouples and pyrometer. Readings from the thermocouples were taken every second, 24 hours a day, and the ten-minute average value was recorded and stored in a text file for each of the thermocouple channels.

3.5.2 Solar Intensity

The solar intensity was measured by the pyrometer, which was also connected to the data logger. Values were recorded and stored similarly to the thermocouple measurements.

3.5.3 Flow

The flow rate was determined by the voltage output on the fan, which was maintained at a constant rate for the testing period. Therefore, data was not continuously logged for the flow rate, but measured at a few instances. Data was collected at two specific flow rates of 0.03121 m^3/s and 0.07378 m^3/s. The majority of the testing was preformed at the higher flow rate. Initially the flow rate was 0.03121 m^3/s for 10 days, and then the fan speed was increased to 0.07378 m^3/s for the remainder of the experiment.

3.6 Experimental Procedure

Before operation, the system was checked for leaks or defects. The collector operated as an open system. Ambient air was drawn into the collector and then exhausted directly to the atmosphere after passing through the fan. The collector was positioned on the single story roof of the U of C weather research station. The roof was flat so the collector was propped up as to orient the collector 70 ^{o} from the horizontal facing due south. The 70 ^{o} angle corresponded to the solar altitude of 22 ^{o} in the beginning of February (Love 2002). The altitude was chosen so as to achieve maximum heating potential during the coldest part of the winter, January-February, and to simulate the practical operation of a system that would remain fixed at one angle for the duration of the winter.

Snowfall and debris were removed from the collector as required. In some instances the fan was simply turned off and the heat radiated from the collector melted the snow and ice. In other cases the material was physically swept off the surface of the collector.

CHAPTER FOUR: Theoretical Background & Analysis

The theory involved in solar heating involves simple heat transfer. An absorber plate receives and absorbs thermal energy from the sun, and then a fluid passed over the absorber receives the heat from the absorber via convection. Thermal solar collectors are heat exchangers using air or a liquid as a working fluid.

Conventional solar air heaters are comprised of a simple flat metal absorber surface, and have efficiencies typically on the order of 40-50%. In contrast, the experimentally tested efficiency of the present collector exceeds 80%. The significant improvement to the efficiency of the present solar air heater is a result of a number of specific alterations made to the collector to address the main areas of energy loss in the conventional air heater. The design considerations for such improvements are explained below. However, firstly the justification for solar air heating in contrast to solar liquid heating, will be explained.

4.1 Working Fluid

In the collector the absorbed solar radiation is transferred to a working fluid in order to provide useful heat for space heating. Both liquid and air are commonly used as working fluids in solar air collectors. The working fluid is chosen for a variety of reasons and each fluid has advantages and disadvantages to its particular usage. In most applications either water or air are used as the working fluid. Advantages and disadvantages of both water and air as the working fluid are listed below (**Table 4.1**).

Table 4.1 Working Fluid Advantages & Disadvantages (Goswami et al., 2000)

Air

Advantages	**Disadvantages**
No freezing problems	Space heating or drying application only
No corrosion problems	Large space required for ducts
Leaks smaller consequence	Larger storage volume required
No heat exchanger needed	Low density and heat capacity
Easy to build	
No phase change of fluid at working temperature [Grupp 1995]	

Water

Advantages	**Disadvantages**
Higher energy density	Freezing problems
Better heat transfer properties	Leakage problems
Better transport properties	Corrosion problems
Space heating and cooling	Heat exchanger required

For a climate where subzero temperatures occur, such as Canada, air has a significant advantage over water as a working fluid. In order to heat water in the colder climates an antifreeze solution would be required as the working fluid, in order to prevent possible freezing of the fluid and consequent bursting of pipes. A heat exchanger would then be required to transfer heat from the working fluid to a space heating application. Heat exchangers significantly add to the complexity and expense of the system.

In addition, any minor leaks in the system would pose a much greater threat to the liquid system, as freezing effects would be amplified. Construction of a flat plate collector can be simplified using air as the working fluid. When using air as opposed to liquid as the fluid, less expensive piping can be used (corrosive effects are greatly lessened using air), also less of a maintenance requirement is needed, and collectors are more forgiving to small leaks, than using a liquid as the working fluid. Simplicity of design and economics are of great importance to the introduction of this new technology to society and therefore, for cold climates such as Canada, using air as the working fluid has significant advantages over a liquid collector. With this in mind, the type of pumping system chosen for the system will now be discussed.

4.2 System Types

There are two general types of thermal solar heating systems: *Active* and *Passive*. Active systems are systems that use a fan or pump to transport the working fluid. Passive systems use natural convection circulation to form what is called a thermosyphon loop.

Passive systems use the buoyant force of the hotter less dense fluid to push the working fluid through the collector. Passive systems have many practical limitations, as they require the collector to be placed lower than the fluid storage tank, as well as operating under low pressure. Normally higher pressures are required for transporting air through ducting of a building, so as to be useful for space heating. The fluctuating flow rate associated with the passive system can also often be very undesirable for heating ventilation air, which is required at a more consistent flow rate.

Passive systems reduce electrical energy use and aid in lowering operating cost for the system, however, the practical limitations of these systems results in inappropriateness for typical space heating applications. Passive systems also operate with higher absorber plate temperatures, which results in greater heat losses in the system. For these reasons, the active systems are more common and were chosen for the present collector. Now that the system type and working fluid have been justified for the system, the importance of the collector orientation to the sun will be mentioned.

4.3 Collector Orientation

The flat surface of solar collectors is to be orientated to the sun in order to reduce the incidence angle of the sun to zero in order to obtain the maximum transmission of solar radiation through the glazing layer. However, the angle to the sun changes significantly during the year (approximately 20 degrees). Therefore, for a larger type of concentrating solar collector, a sun tracking system is used to maintain a zero incidence angle of the collector to the sun, by constantly adjust the position and tilt of the collector. This greatly increases the cost of the system; therefore typically for flat plate collectors a fixed system is incorporated.

For a fixed solar collection system a close approximation of orientation is to fix the collector due south at 15 degrees plus the latitude, from the horizontal. The more northern a system is located from the equator, the less sensitive east/west orientation becomes regarding the due south facing of the collector. For the present collector, the collector orientation angle was chosen to be 70 degrees from the horizontal, facing due south. The solar altitude at the end of January was approximately 20 degrees. Therefore, the orientation was to maximize the collection during the colder winter months. As the months extend from January, due to the change in solar altitude, less solar energy becomes perpendicularly incident on the collector face. It should be noted that the sun rises to approximately 45 degrees by the beginning of April (Love 2002), which comprises only a 25-degree deviation from the design angle fixation. The orientation of the collector to the sun is essential to maximize the effectiveness of a solar collector, as well as having a proper glazing layer. In the next section an understanding of the function and role of a glazing layer will be explained.

4.4 Analysis

The majority of solar thermal collectors have a glazing cover (usually glass). The glazing layer provides a surface that is vastly permeable to incoming short wave solar radiation, but is opaque to long wave radiation (heat radiated from the absorber plate). The glazing layer acts as a trap, allowing the sun's short wave radiation in, but blocks radiated heat (long wavelength) given off by the absorber from escaping. **Figure 4.1** shows a schematic diagram of the energy balance for a simple collector.

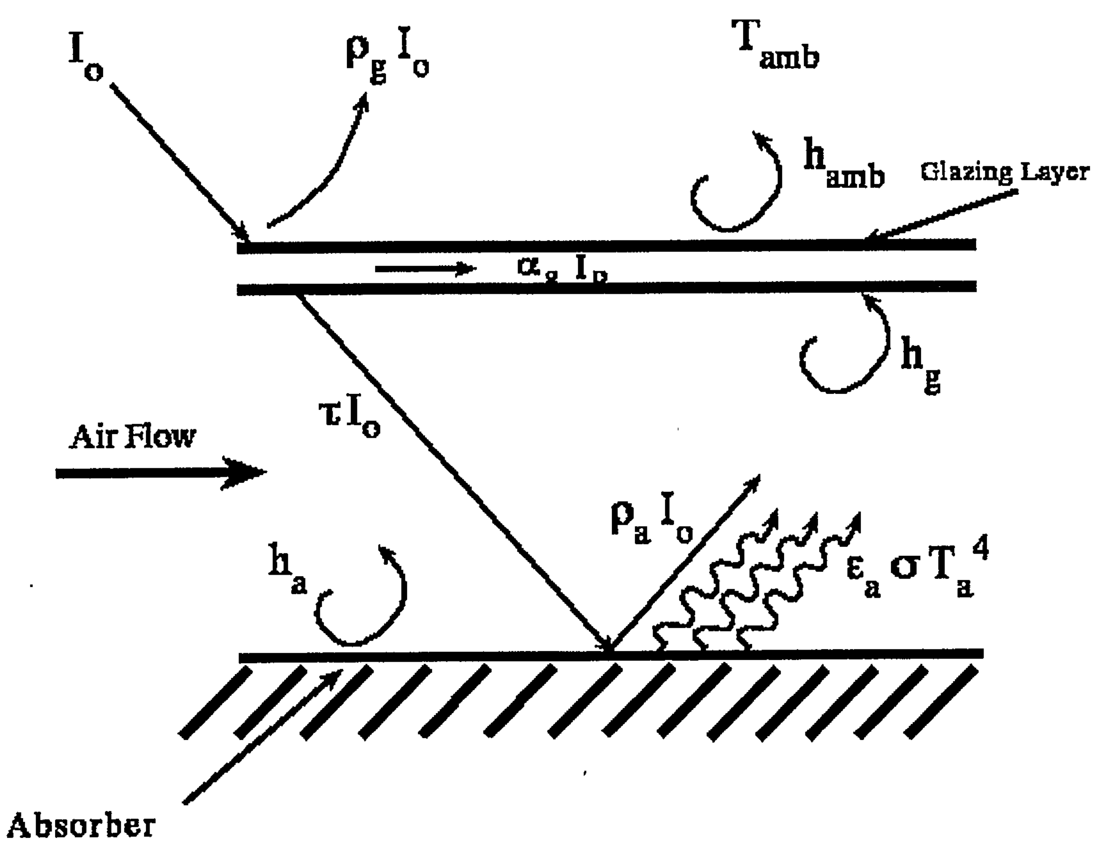


Figure 4.1 Schematic Diagram of Energy Balance in Solar Collector

The vast majority of short wave length radiation is transmitted through the glazing layer, τI_o. The absorber plate or porous media absorbs this radiation. As the absorber material is heated, the material reradiates heat (long wavelength radiation, $\varepsilon_a \sigma T_a$), which cannot pass through the glass. Therefore, the glazing layer traps long wave thermal radiation emitted from the hot absorber, inside the collector duct.

Glass is the most common glazing material as it is a common readily available material that transmits about 90% of the short wavelength solar radiation and blocks the vast majority of the long wavelength radiation. To increase the overall collector efficiency, two glass layers can be used.

The two layers on the present collector form an additional channel that the air flows through before entering the porous material cavity. In the present project a design was considered to capture heat losses from the glazing layer immediately above the porous media absorber. This was done by adding a second pane of glass above the initial glass layer so air may first pass through the glass layers, then pass through the porous matrix **(Fig 1.4f)**.

The inner most glazing layer provides a surface to reflect long wavelength radiation from the absorber material (steel wool). However, as this inner glass layer blocks the long wave radiation inside the collector, the glass layer subsequently becomes heated. Much of the conventional collector's losses are a result of the heating of this glass layer, which causes significant convection losses to the ambient. In the present two-pass system, the inner glass layer acts as an absorber plate for the first air pass, thereby collecting much of the heat that in conventional collectors was lost to the ambient. This effect significantly adds to the higher efficiency of the proposed collector. The last, but most significant increase in the overall efficiency of the collector, results from the use of a porous matrix absorber.

4.5 Porous Material

As cited in the previous section (Literature Review, Chapter 2) one of the largest concerns in solar air heating is transferring the heat from the absorber to the air stream efficiently. Much work has been done in attempting to increase the effectiveness of the energy exchange between the absorber and airflow via numerous shaped fins, ribs, and porous materials. Efficient heat exchange from the absorber plate results in a lower temperature of the absorber plate and therefore results in less conductive losses in the system, overall smaller collectors, and higher possible air temperatures (Sharma 1991).

The past work using fins and ribs has made advances in the heat transfer from the absorber, however, the cost and complexity of the collector is increased and much room is still left to increase the effectiveness of the heat transfer. Surface area is the key concern to facilitating effective convective heat transfer from the absorber, although collector size is desired to be minimized as well as avoidance of complex manufacturing of finned absorber plates.

Therefore, for the solar air heater of concern, the absorber material used was a porous matrix of steel wool. The steel wool provides an enormous increase in absorber plate surface area per unit volume, compared with the conventional flat plate solar air heater. The increased area available for convection results in a greater efficiency in heat transfer which largely accounts for the high efficiency of the collector. The steel wool also has the advantage of being much easier to manufacture in comparison to the ribbed and finned absorber plates.

The increase in absorber surface area allows for a lower absorber temperature and therefore, less convective and radiative losses through the glazing layer. In order to further avoid heat losses through the glazing layer a 2.5 cm air gap was ensured surrounding all surfaces of the porous bed. This allowed greater heat transfer to the air, and restricted the heat transfer to the glass layer. The porous media greatly increased the efficiency of the heat transfer between the air and the absorber, which resulted in a more efficient system.

4.6 Governing Heat Transfer Equations

The present collector has proven to have exceptionally high efficiencies as a result of a number of different design characteristics previously discussed. The following section will explain the methodology used to determine the effectiveness of the collector. Calculations used for the analysis of the system are basic heat transfer equations. **Figure 4.2** depicts the nomenclature used for the heat transfer analysis.

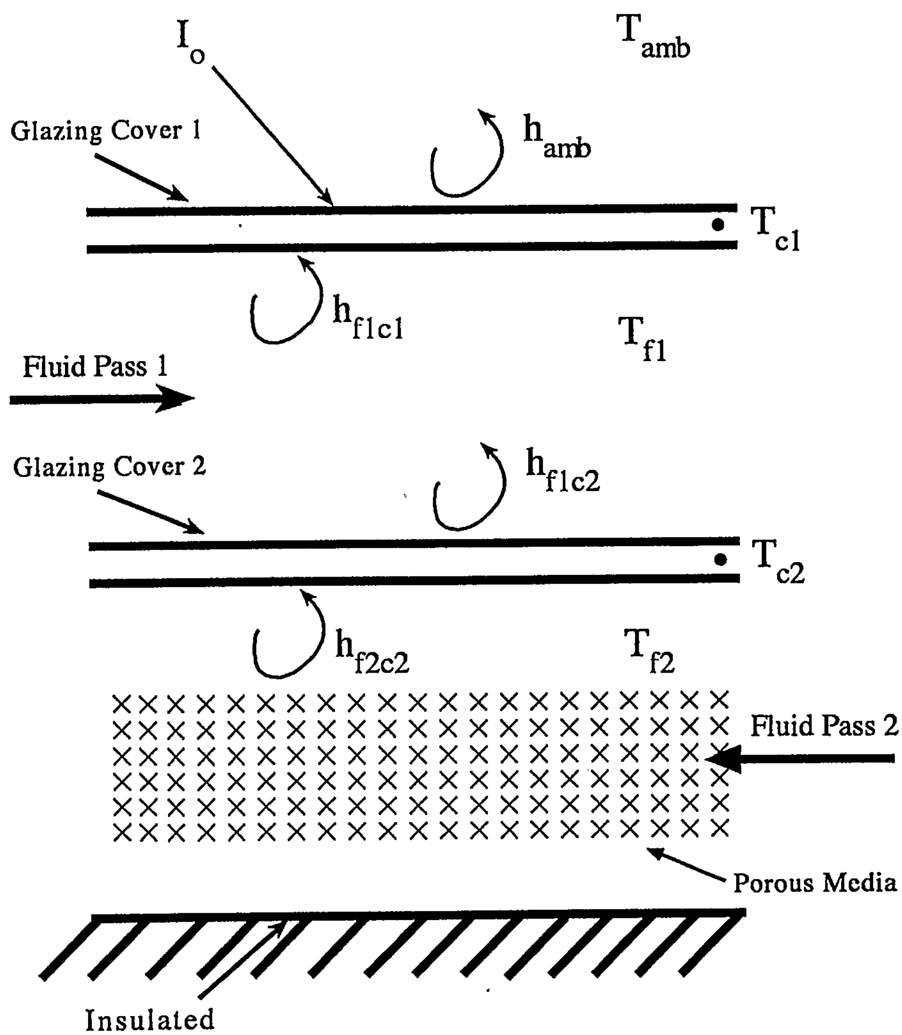


Figure 4.2 Analysis of Heat Transfer in Collector

The following equations present energy balances for the collector operating with unsteady state conditions:

For the top glass cover:

(2) $I_o\alpha_c = h_{amb}(T_{c1} - T_{amb}) + h_{f1c1}(T_{c1} - T_{f1}) + h_r(T_{c1} - T_{c2})$ W/m^2

For the air in the first air pass:

(3) $\overset{o}{m} C_p \dfrac{\delta T_{f1}}{\delta x} = h_{f1c1}(T_{c1} - T_{f1}) + h_{f1c2}(T_{c2} - T_{f1})$ W/m^2

For the second, lower glass cover:

(4) $I_o\alpha_c\tau_c = h_r(T_{c1} - T_{c2}) + h_{f1c2}(T_{c2} - T_{f1}) + h_{f2c2}(T_{c2} - T_{f2}) + h_r(T_{c1} - T_p)$ W/m^2

For the air flowing through the collector bed, heat is transferred via convection with the porous media. Heat transfer through porous media is of very complex nature and generally an adjustment to the actual fluid thermal conductivity is done to account for the heat transfer properties of the media and fluid. The effective thermal conductivity of the system is a function of porosity and the thermal conductivity of both the air and the solid material. The assumption is also made that the solid matrix and air stream are in thermal equilibrium, justified by the very large heat transfer coefficient between the media and air, on the order of 4 x 10^5 W/(m^3K) (Mohamad 1997).

Therefore, the second air pass through the porous media:

$$(5)\qquad \overset{o}{m} C_p \frac{\delta T_{f1}}{\delta x} = k_{eff} \frac{\delta^2 T_{f2}}{\delta x^2} + h_{f2c2}(T_{c2} - T_{f2}) + U_a(T_a - T_{f2}) + I_o \alpha_p \tau_c \tau_c \qquad W/m^2$$

Heat transfer equations used to calculated the overall increases in air temperature and thermal efficiency are presented below:

The heat gain to the air can be calculated using the formula:

$$(6)\qquad Q_{out} = \overset{o}{m} C_p (T_{out} - T_{in}) \qquad W$$

Expressed in terms of an energy balance:

$$(7)\qquad I_o A = \overset{o}{m} C_p (T_{out} - T_{in}) + losses \qquad W$$

Therefore, the thermal efficiency of the collector is found from:

$$(8)\qquad \eta_{th} = \frac{\overset{o}{m} C_p (T_{out} - T_{in})}{I_o A}$$

This section has given an understanding of the physics and heat transfer phenomenon in the solar air heater. In the next chapter the results of the collector testing will be discussed.

CHAPTER FIVE: Results & Discussion

This section will present and discuss the data collected over the course of the project. The data has shown very encouraging heating output from the collector. The collector has great potential to change the technology in the solar air heating industry, as well as open up new heating applications for solar energy. The parameters measured and to be discussed are the outlet air temperature, ambient air temperature, collector bed temperatures, and the solar intensity. These values were subsequently used to find the thermal efficiency of the collector. Firstly, the data from the temperature profiles within the porous absorber bed will be shown for the two flow rates at which the testing occurred. This will be followed by the remainder of the data from the lower flow rate testing, followed by the presentation of the results collected at the higher flow rate testing.

5.2 Thermal Capacity of the Collector

It should be addressed, that measurements were taken every second, but the average value recorded was over a ten minute interval. Due to the sometimes-variant nature of the weather, mainly the solar intensity due to periodic cloud cover etc, the efficiency values calculated over an individual ten-minute interval may be misleading. For example, the collector box and porous material become heated during midday operation, but periodically a cloud passes over and casts a shadow on the collector for a few minutes. In this situation the solar intensity measurement records a very low value, yet due to the heat capacity of the porous material and collector box, a much less significant drop in the outlet temperature will be observed. In this occurrence, a calculation of the thermal efficiency of the system, based on incoming solar radiation (very low) and change in air temperature through the collector (still large), would be quite misleading. This indicates the system has a slower response to solar intensity fluctuations, which is a very desirable attribute for a practical solar air heater. However this effect results in periodic data collected being of no practical significance. This phenomenon, resulting from the thermal response of the system, can be seen in **Figures 5.1** and **5.2**.

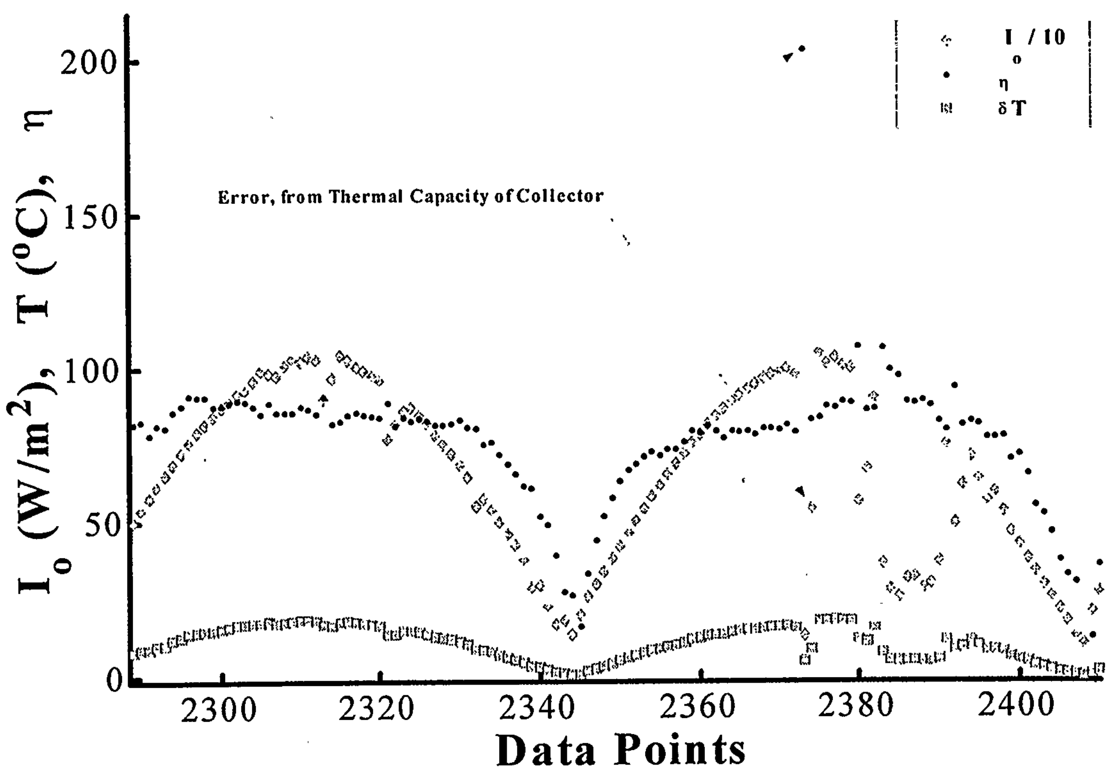


Figure 5.1 Inaccuracies Resulting from Rapid Solar Intensity Changes, for airflow of 73.78 L/s

From the above figure it can be seen that under reasonably consistent solar radiation, the collector thermal efficiency is also consistent. However, as discussed, rapid changes in the solar intensity such as in **Fig. 5.1** near data point 2372, where the measured solar radiation average dropped from 1000 W/m^2 to 100 W/m^2 in a ten-minute interval (likely due to cloud cover), resulted in a calculated thermal efficiency of approximately 200%. This is the result of the heat capacity of the porous material and collector box transferring their stored heat to the incoming air, despite the little incoming solar radiation restoring the heat. These transient stages are common during days with clouds, but produce misleading efficiencies of the solar air heater. **Figure 5.2** also depicts similar results of the collector during a consistently transient solar day.

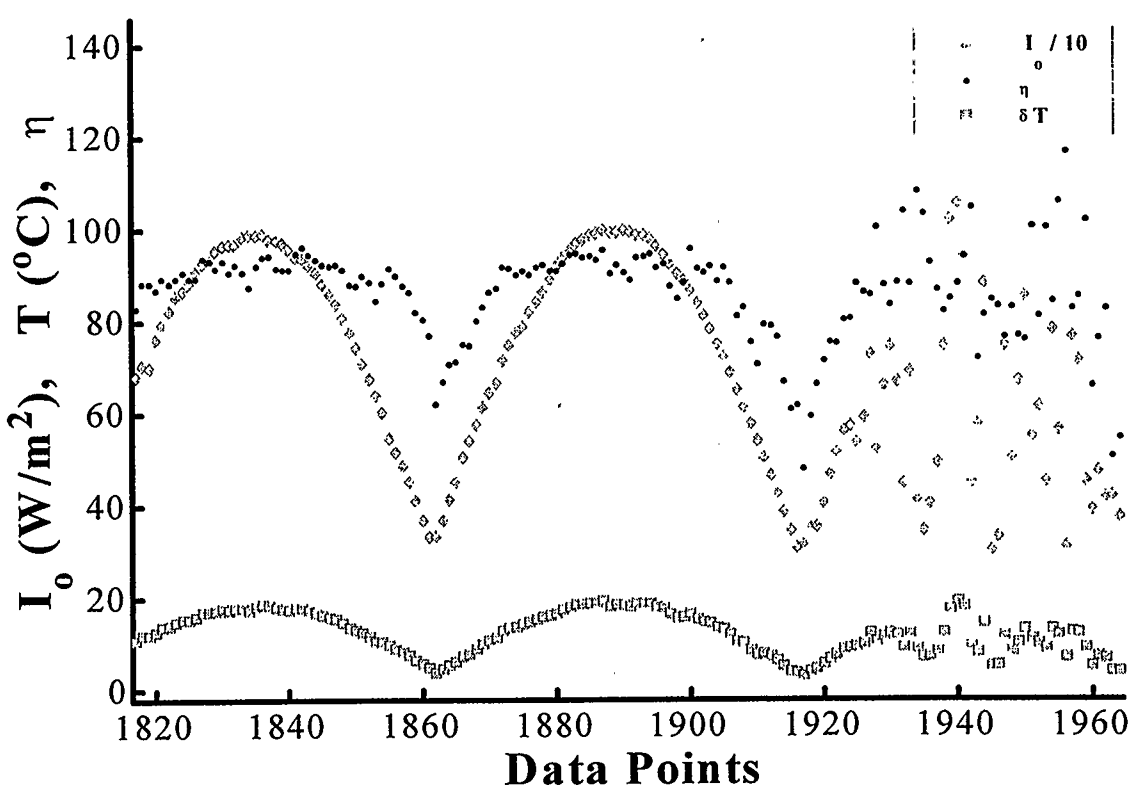


Figure 5.2 Unsteady State Performance of Collector, for airflow of 73.78 L/s

Viewing **Figure 5.2**, it can be seen that continuous changes in the solar insolation results in corresponding inconsistent and misleading thermal efficiencies from the collector. The first two sinusoidal curves for solar intensity (depicting two days of relatively cloud free weather) display consistent collector performance. However, the next day shows inconsistent solar intensity and also inconsistent efficiencies calculated. Due to the nature of the data logging and averaging over a ten-minute time interval, it can be seen that the efficiency calculations are not an accurate reflection of the collector performance.

It should also be noted that the temperature output from the collector has smaller variations than the solar intensity measurement. This is a result of the thermal capacity of the collector (porous material and collector box), which retains significant quantities of heat to maintain high outlet air temperatures even when the solar radiation levels fluctuate for a short period of time.

To observe an accurate reflection of the solar collector's thermal performance, data collected during more consistent solar intensity should be studied. Therefore, data with obvious errors in efficiency calculations, as well as data collected under low and negligible solar intensity have been removed in order to provide a more accurate presentation. Due to the fact that cloud cover and similar transient behavior of the collector occurred frequently, often testing days had a number of data points which were necessary to remove to provide meaningful data. With this data removed, it is necessary to specify that the x-axis of the graphs represents time, but is presented as *data points*, as it is not a continuous time interval. Figures individually specify the criteria for the minimum levels of solar intensity that the data points were recorded. The minimum levels of solar intensity used to display the data points are 300, 500, 700, and 900 W/m^2. Therefore, for each of these cases all data points with a solar intensity value less than the specified minimum level, were removed. Consequently, unless specified, the x-axis label for figures in this section is not a continuous time interval, but a chronological arrangement of data collected at ten-minute time intervals, (referred to as "*data points*"), with the specified solar intensity and reasonable efficiency restrictions. With this in mind, the presentation of the data for the temperature profiles within the collector bed will now be presented, followed by the data from the low and then high flow rate testing.

5.1 Collector Bed Temperature

The collector had five thermocouples evenly spaced throughout the length of the porous bed. These thermocouples provide insight to the potential and workings of the collector. **Figure 5.3** shows the various temperatures along the collector bed for a typical day during the lower airflow rate testing (31.21 L/s).

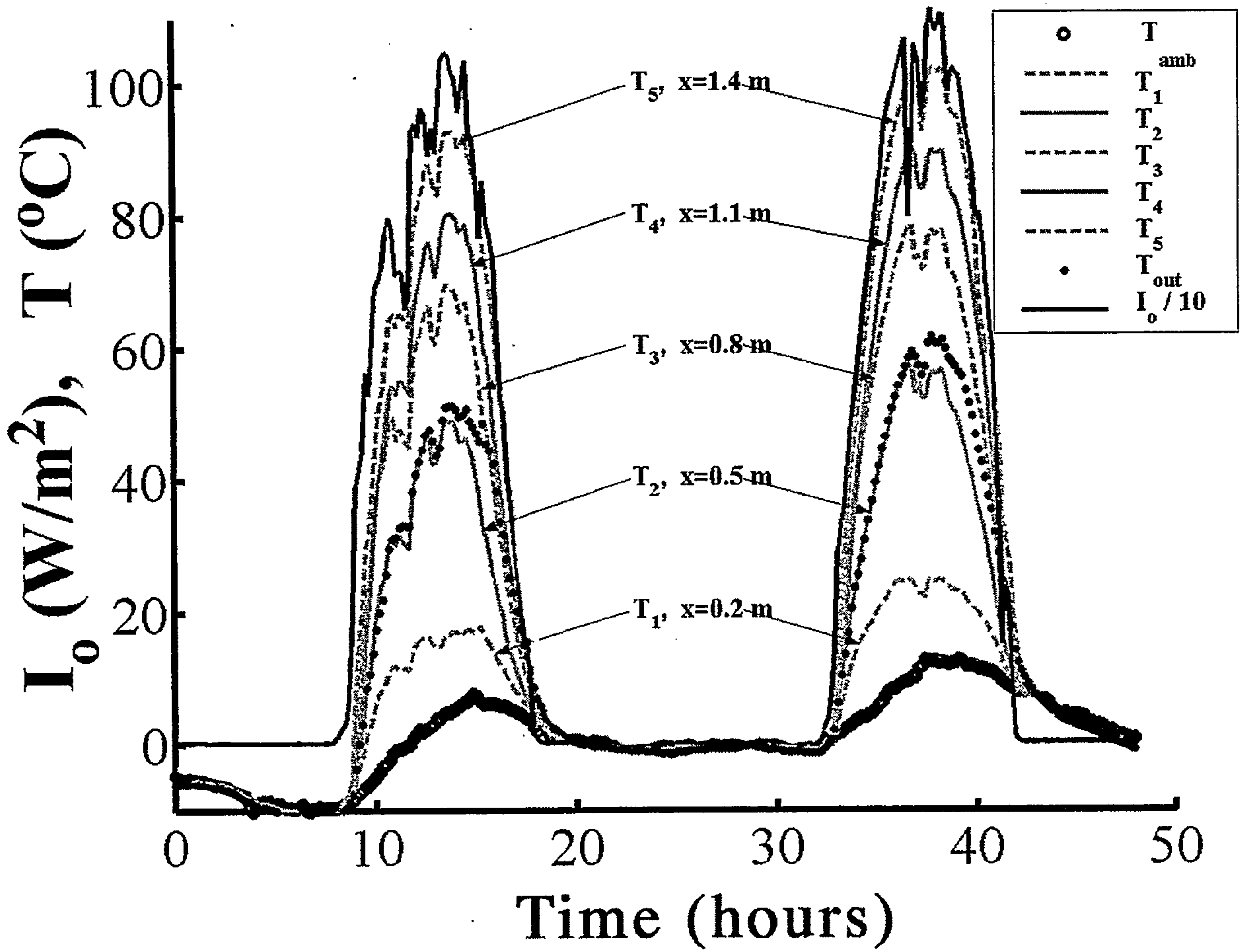


Figure 5.3 Porous Bed Temperature Distribution with 31.21 L/s Airflow

Figure 5.3 shows that the outlet temperature is approximately 50-60% of the maximum temperature achieved in the porous bed. Therefore, identifying a potential for an increased amount of heat to be extracted from the bed. Therefore, a higher flow rate was chosen to continue testing. The second testing occurred at an airflow rate of 73.78 L/s, or 0.07378 m^3/s. The increased flow rate increased the heat transfer coefficient between the air and absorber by increasing the air velocity acting on the absorber surface, and therefore increasing the turbulence in the porous matrix. **Figure 5.4** shows the absorber bed temperatures during the higher air flow rate testing, under solar intensity conditions that are similar to those in **Figure 5.3**.

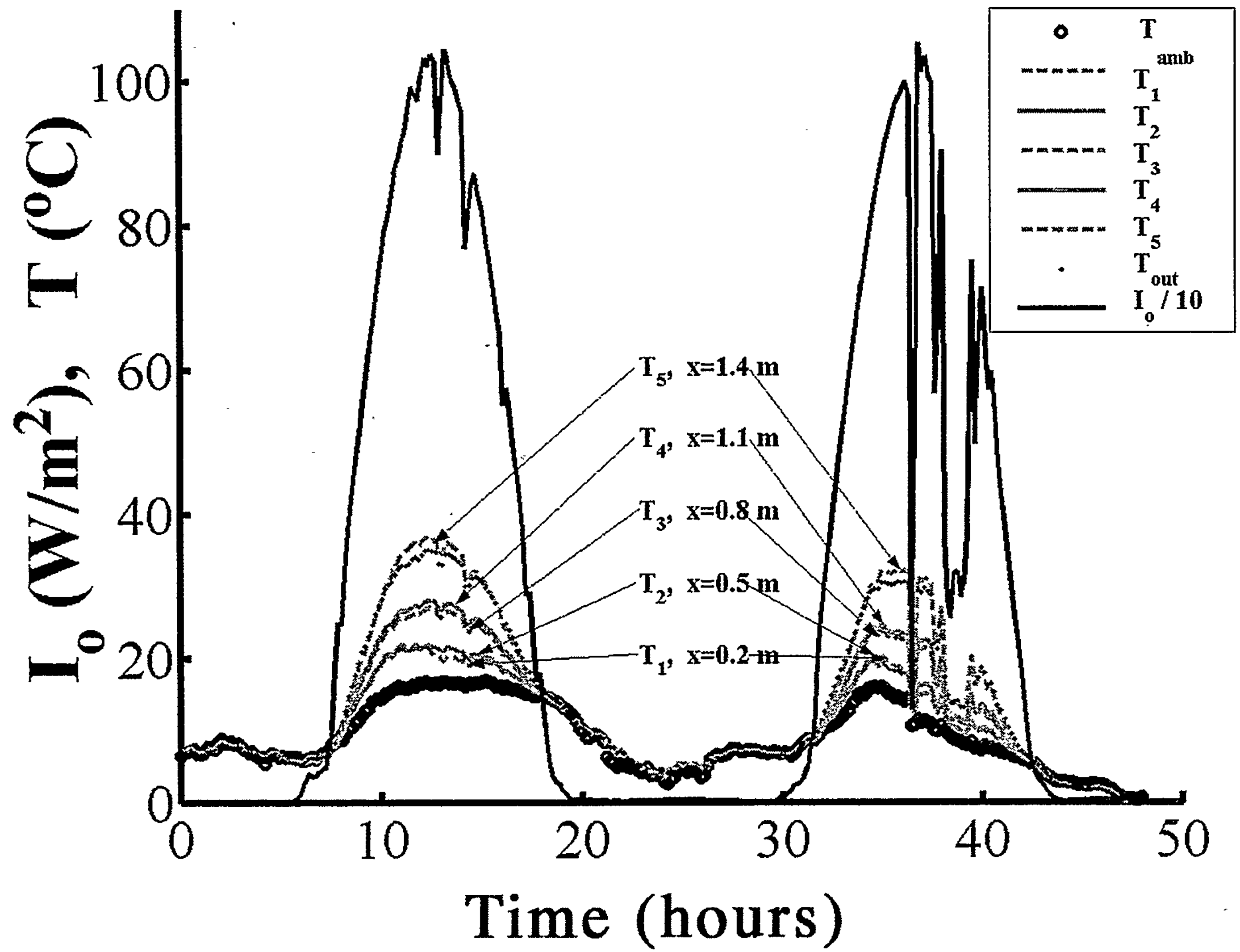


Figure 5.4 Porous Bed Temperature Distribution with 73.78 L/s Airflow

Viewing **Figure 5.4** it can be seen that the increase in airflow greatly reduced the collector bed temperature in comparison to the temperature in the lower airflow testing. This also resulted in the outlet air temperature being very similar to outlet end temperature of the porous material. The higher airflow results in a more efficient heat exchange between the porous material and the air stream. The reduction in bed temperature reduces heat losses through the glass layer. The following section will discuss in more detail the temperature and efficiency results from collector, obtained at the lower airflow rate.

5.3 Lower Flow Rate Results

5.3.1 Temperature Data

The initial testing of the system was at the lower airflow rate. The system was operated with a constant flow rate of 31.21 l/s or 0.03121 m^3/s for 9 days during mid February 2002. **Figures 5.5-5.8** depicting the temperature increases achieved by the collector operating with the 31.21 L/s flow rate.

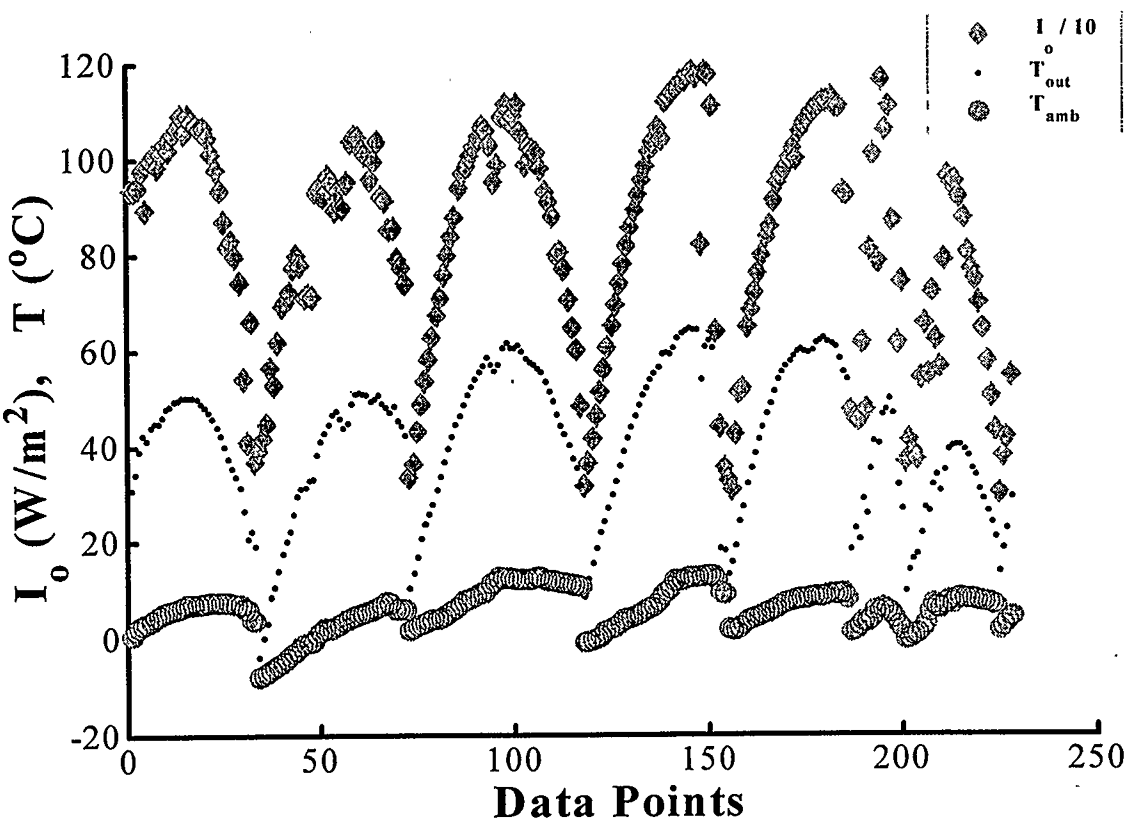


Figure 5.5 Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 300 W/m^2, for airflow rate of 31.21 L/s

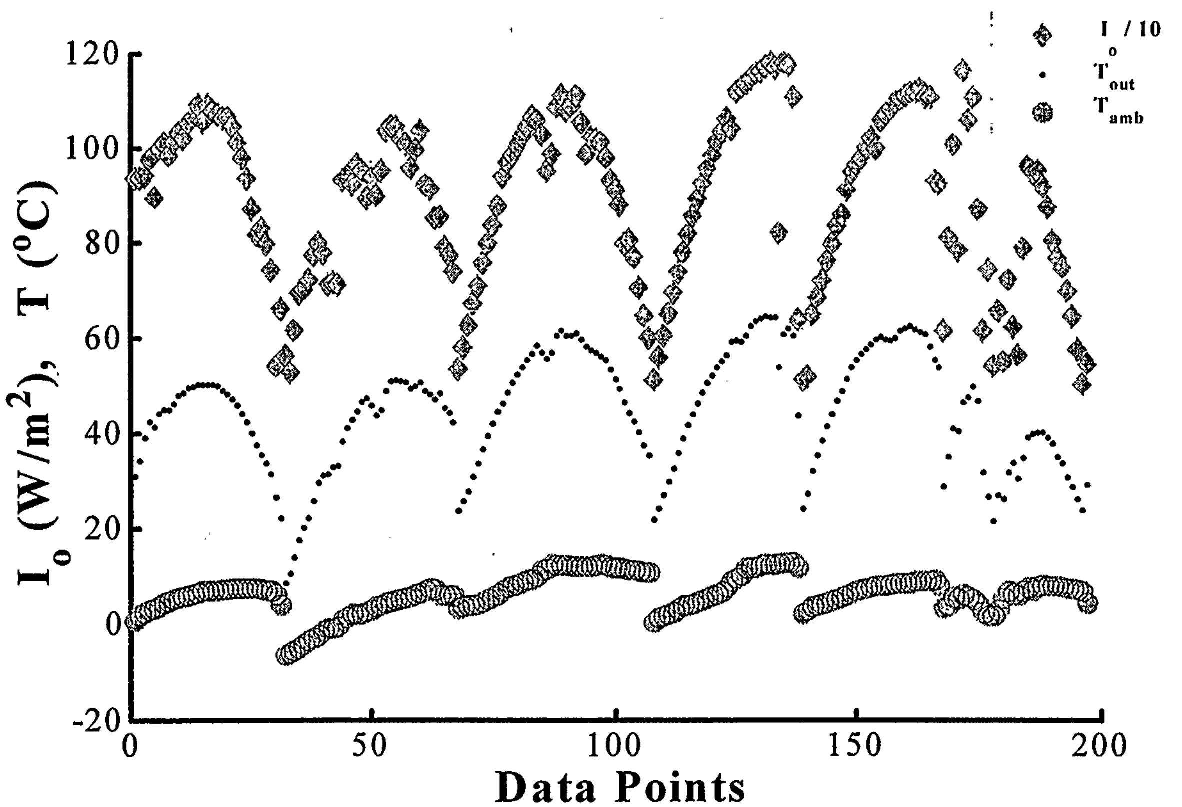


Figure 5.6 Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 500 W/m^2, for airflow rate of 31.21 L/s

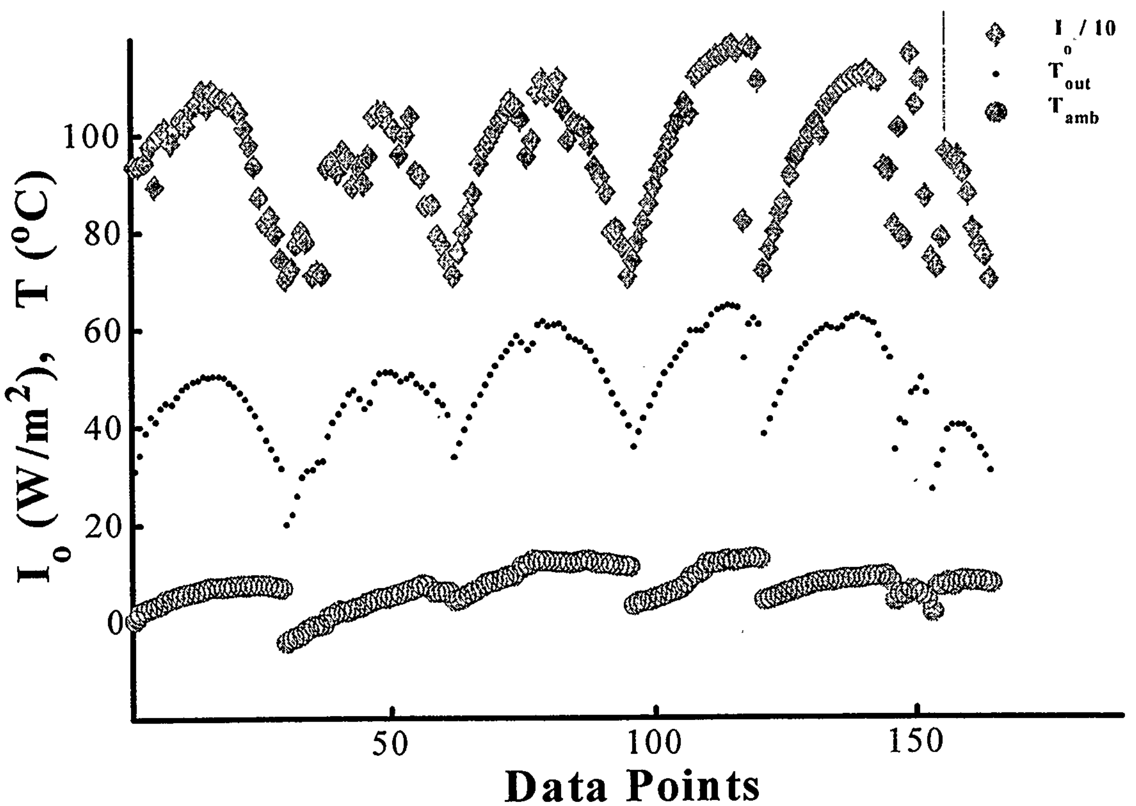


Figure 5.7 Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 700 W/m², for airflow rate of 31.21 L/s

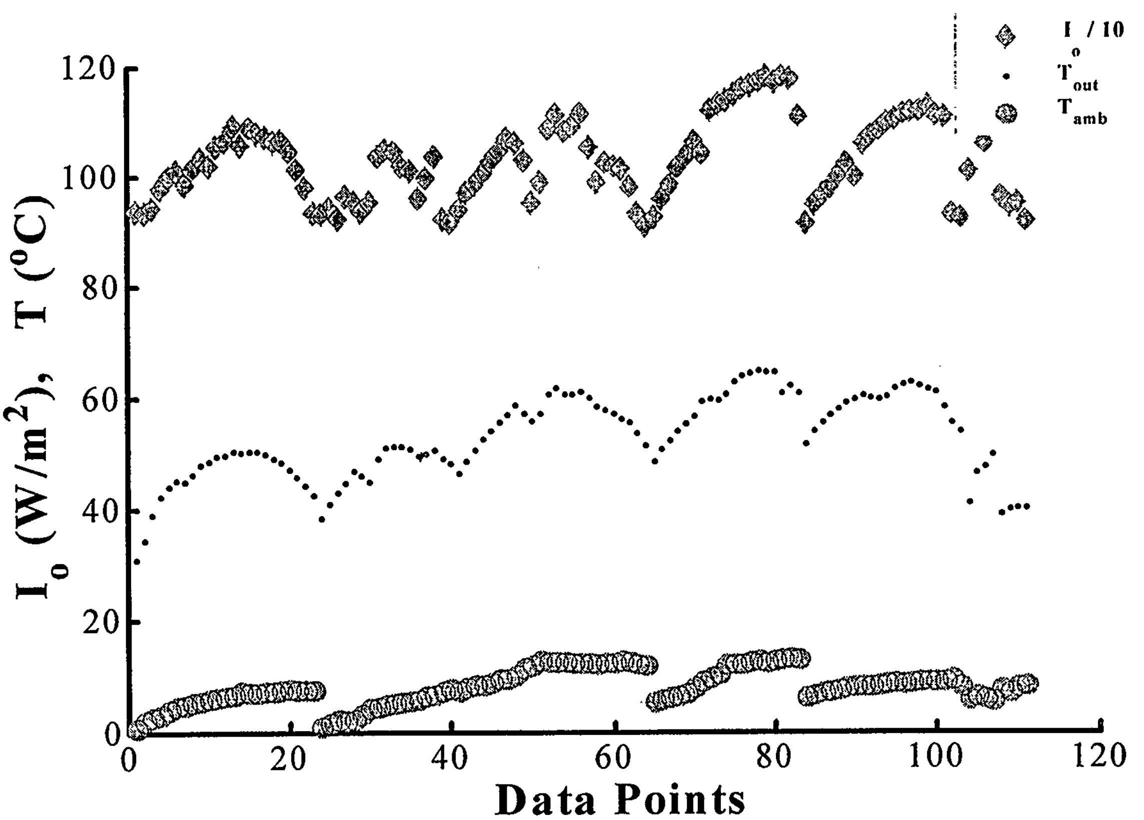


Figure 5.8 Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 900 W/m^2, for airflow rate of 31.21 L/s

As expected, the previous figures show a very strong correlation of the collector outlet air temperature with the solar intensity. As the solar intensity changes, the outlet air temperature similarly reacts to the change. It can be seen from **Figure 5.5** that solar insolation levels of 300 W/m^2, provide little useful temperature gain in the outlet air stream with the given flow rate. Whereas, **Figure 5.8** shows consistent high output temperatures, between 40 and 60 ^{o}C, during sunny days with a solar intensity greater than 900 W/m^2. Temperatures of up to 65 ^{o}C where recorded, with an inlet temperature of approximately 13 ^{o}C.

5.3.2 Efficiency

The following figures have shown the data that was used to determine the temperature increase across the collector and the collector overall thermal efficiency. **Figures 5.9-5.12** depict the thermal efficiency of the collector for various solar intensity levels.

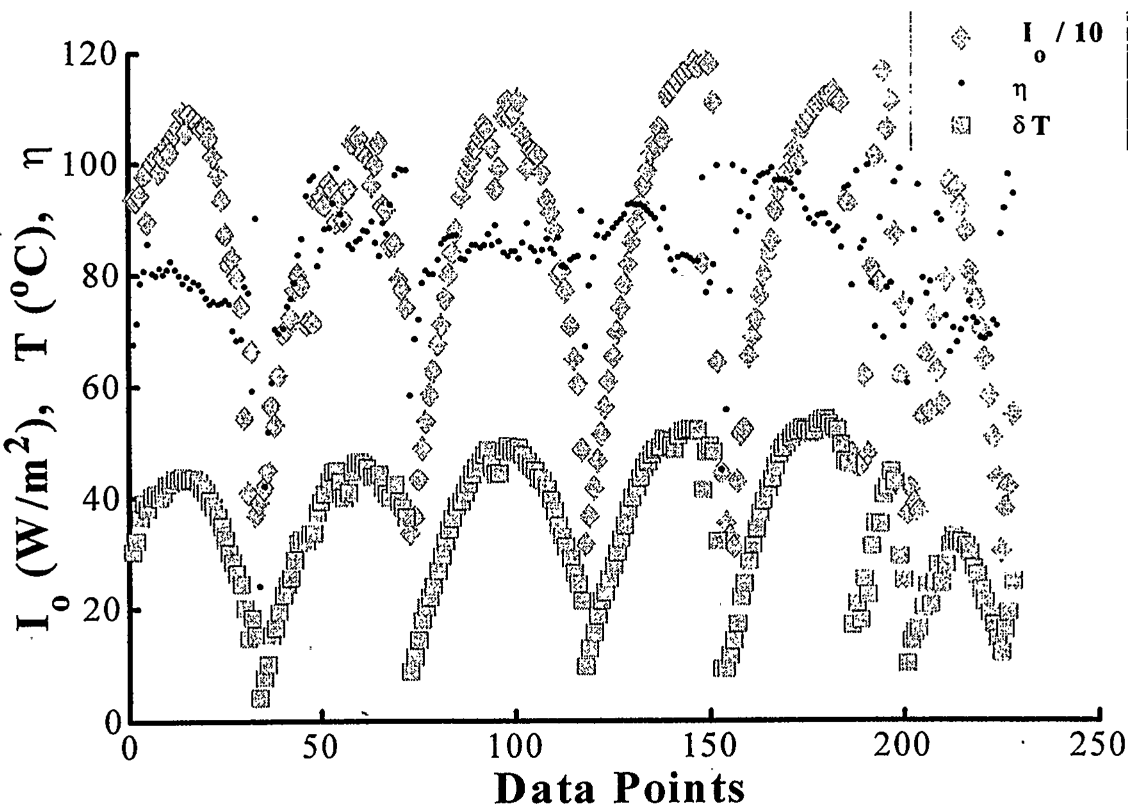


Figure 5.9 Collector Thermal Efficiency with Solar Intensity > 300 W/m^2, with 31.21 L/s Airflow

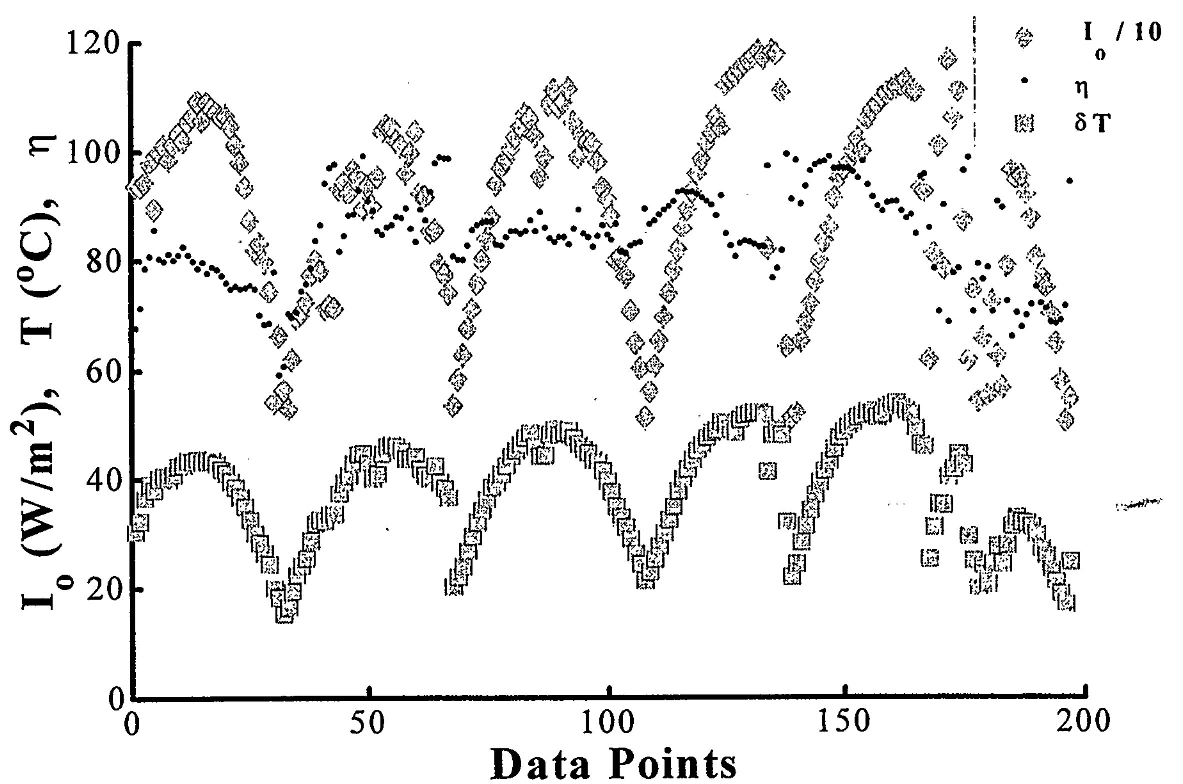


Figure 5.10 Collector Thermal Efficiency with Solar Intensity > 500 W/m^2, with 31.21 L/s Airflow

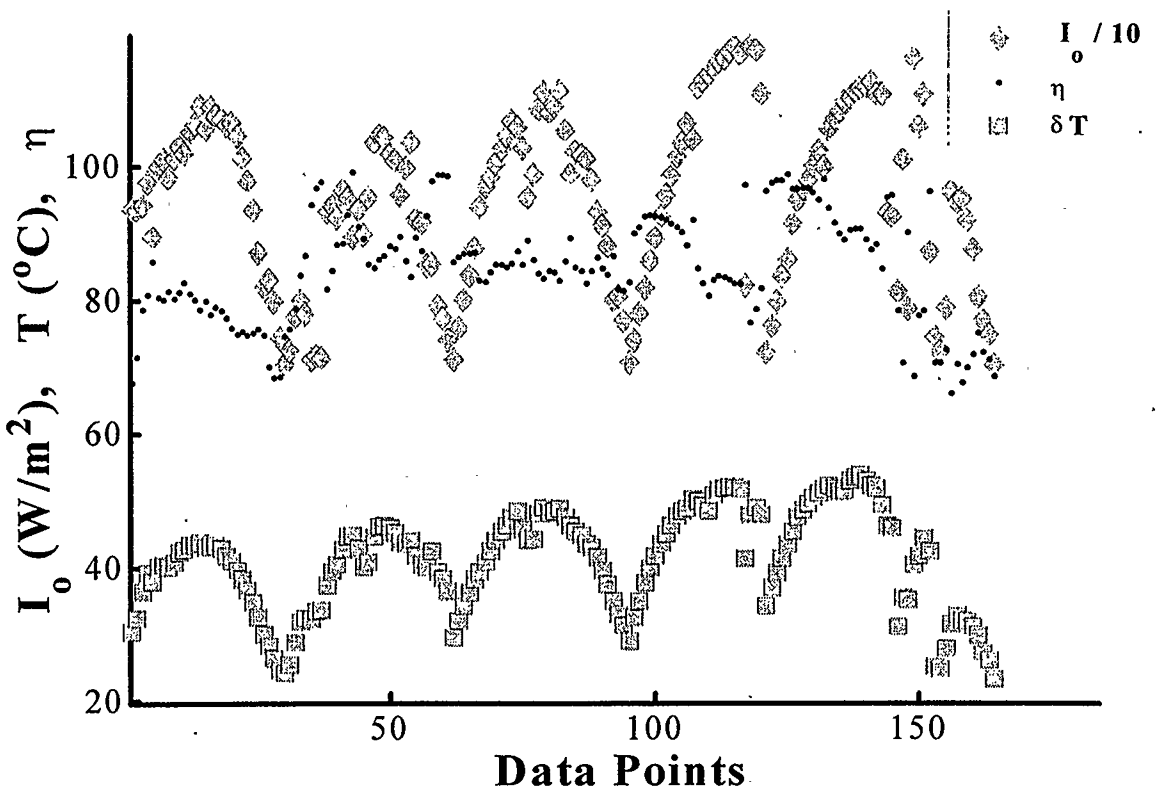


Figure 5.11 Collector Thermal Efficiency with Solar Intensity > 700 W/m², with 31.21 L/s Airflow

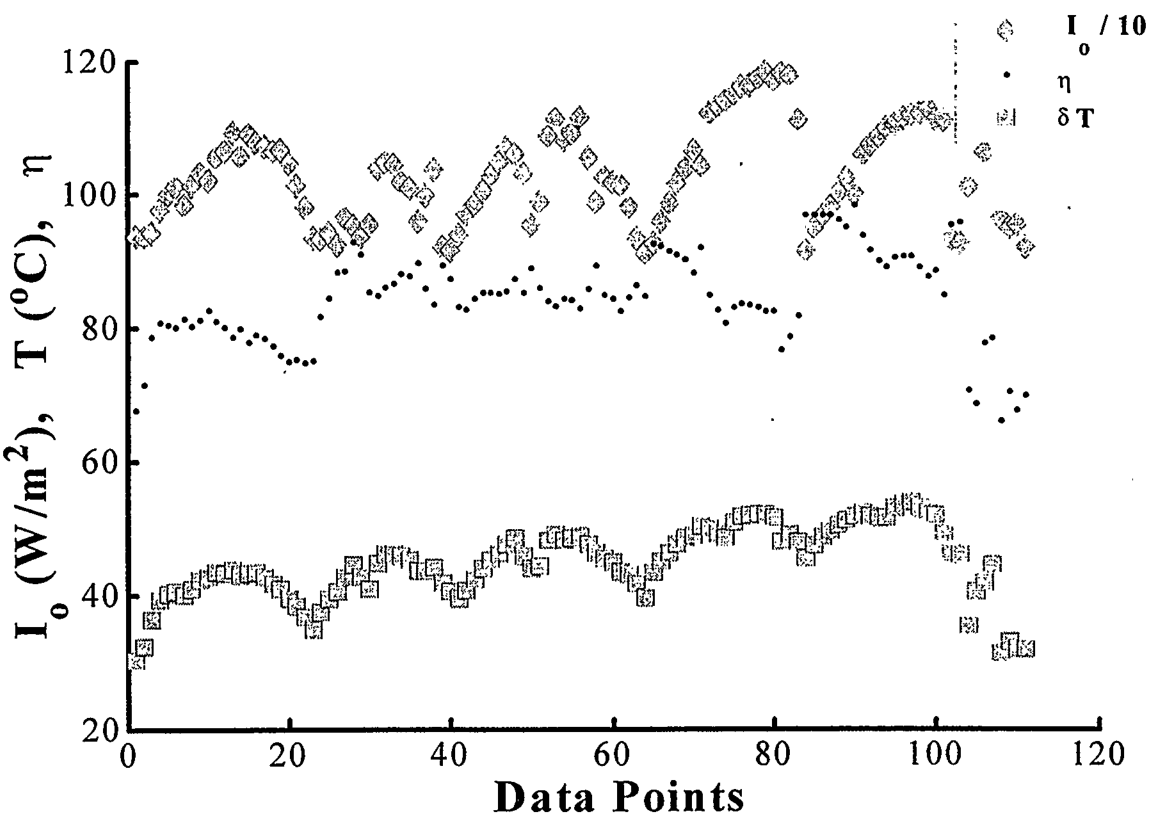


Figure 5.12 Collector Thermal Efficiency with Solar Intensity > 900 W/m², with 31.21 L/s Airflow

Viewing **Figures 5.9 - 5.12** it can be seen that the average thermal efficiency of the collector is approximately 85%. It is also seen that the data becomes increasingly consistent as the solar intensity increases. This is explained by knowing that for a typical day the solar intensity increases through the day until midday. Therefore, the lower solar intensity results include the transition phases of the collector's operation. These transient stages of operation include the more rapid changes in solar intensity as the sun rises and sets in the sky, as well as intermittent cloud cover and other transient stages of solar radiation. These changes do not allow the collector to record steady state data. Therefore, efficiency data is increasingly accurate as the solar intensity increases to midday, where the solar intensity tends to change little for a significant amount of time.

The present solar air heater operates with very high efficiencies, even at the low flow rate of 31.21 L/s. The average efficiency for the collector's operation can be seen in **Table 5.1.**

Table 5.1 Average Collector Thermal Efficiency of Collector with Airflow of 31.21 L/s

Solar Intensity above, W/m^2	**300**	**500**	**700**	**900**
Average Collector Efficiency	83.4	84.5	84.9	84.4

With a very high flow rate many collectors are able to operate with reasonably high efficiencies as the high air velocity naturally increases the heat transfer coefficient. However, under lower flow conditions, such as tested, it is a great improvement to increase the efficiency of this collector past that of conventional collectors, even at high airflow rates.

5.4 Higher Air Flow Results

5.4.1 Temperature

As noted earlier in the chapter, it was determined that with the lower airflow of 31.21 L/s, there was still a significant difference between the porous bed temperature and outlet air stream temperature. Therefore, it was chosen to increase the flow rate to determine the maximum useful heating potential of the collector. The airflow rate was increased to 73.78 L/s. The following is a presentation of the collector outlet temperature data versus the solar intensity collected at this higher airflow rate from March 1 - May 1 2002.

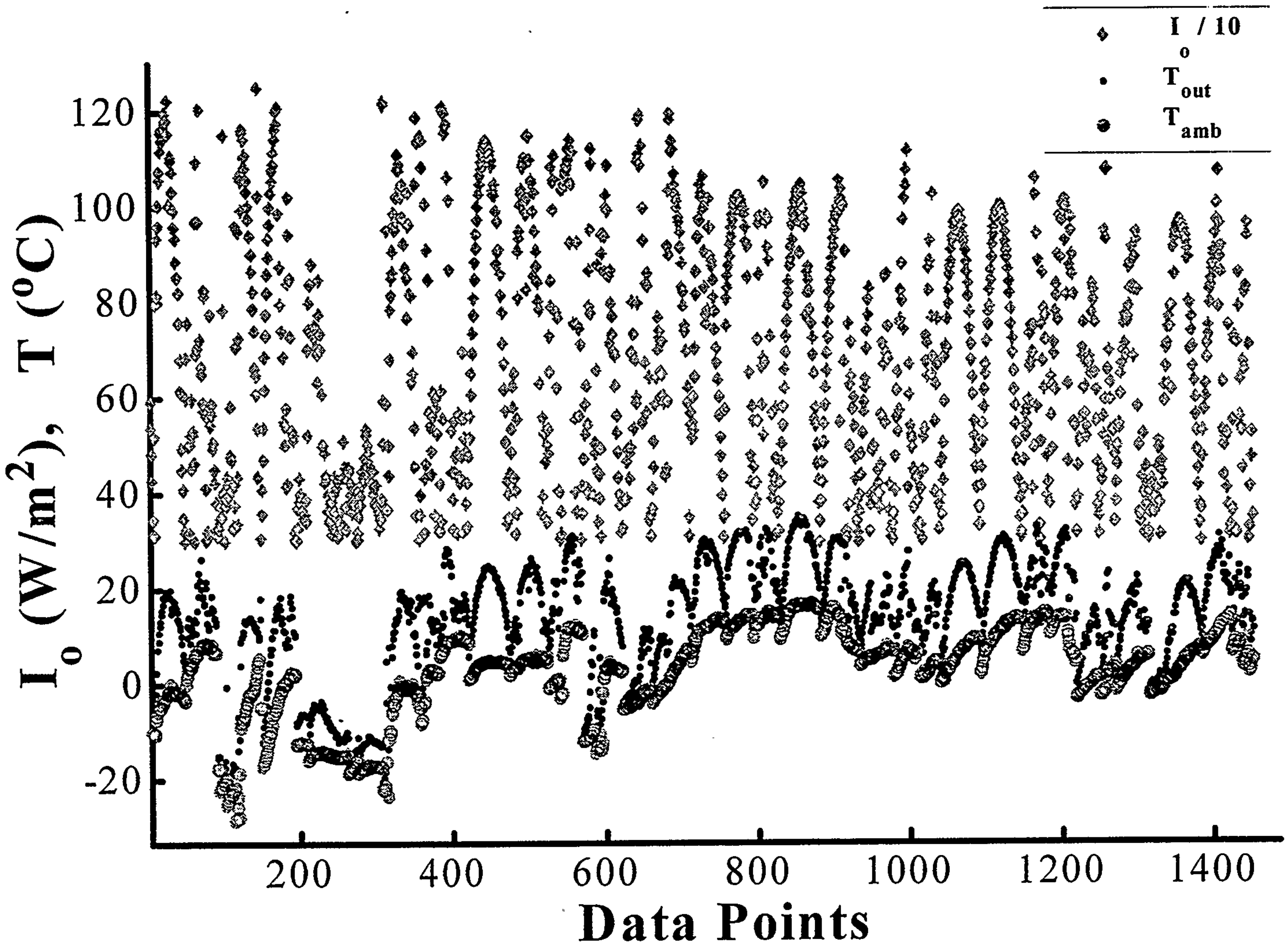


Figure 5.13Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 300 W/m2, for airflow rate of 73.78 L/s

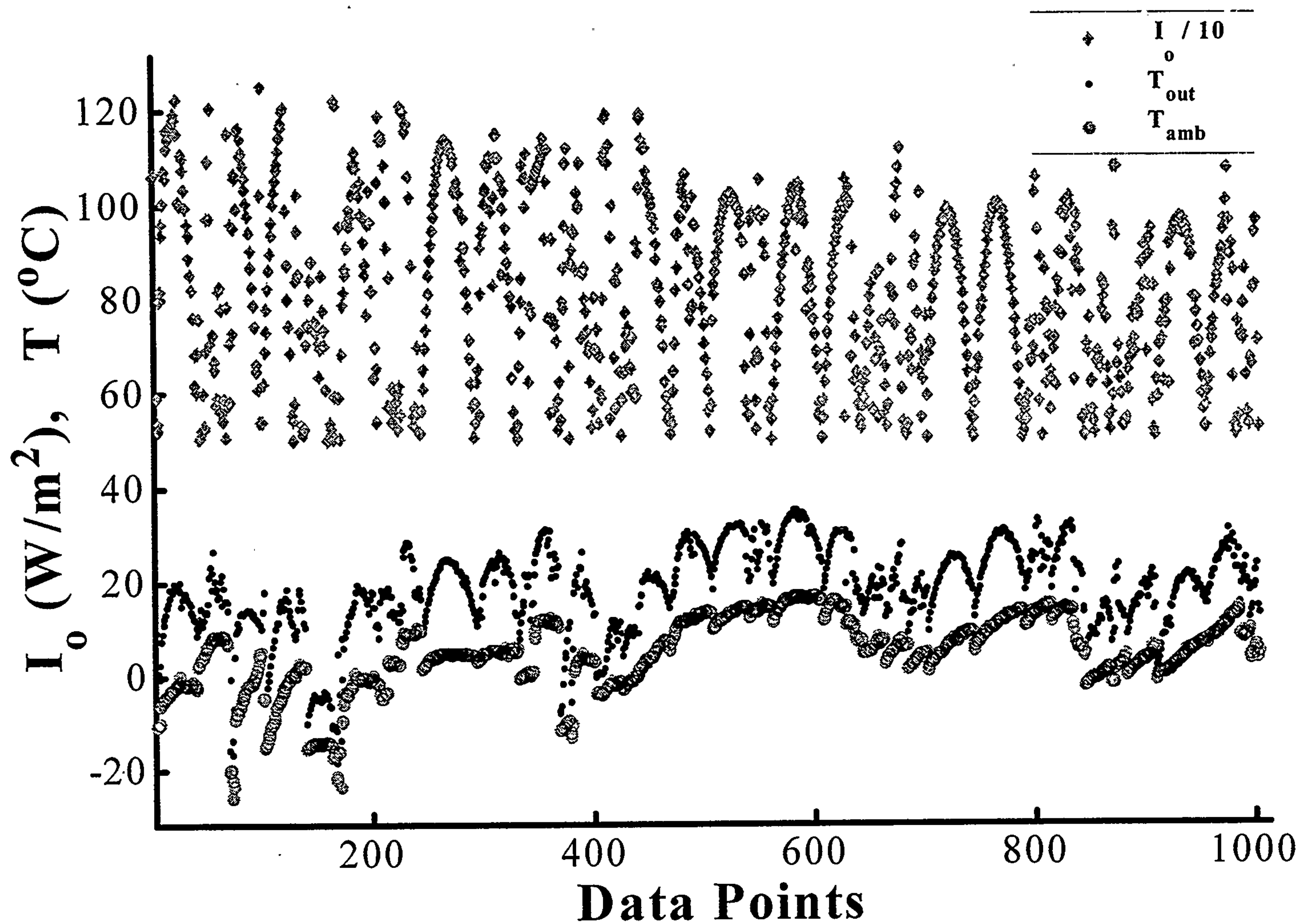


Figure 5.14 Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 500 W/m², for airflow rate of 73.78 L/s

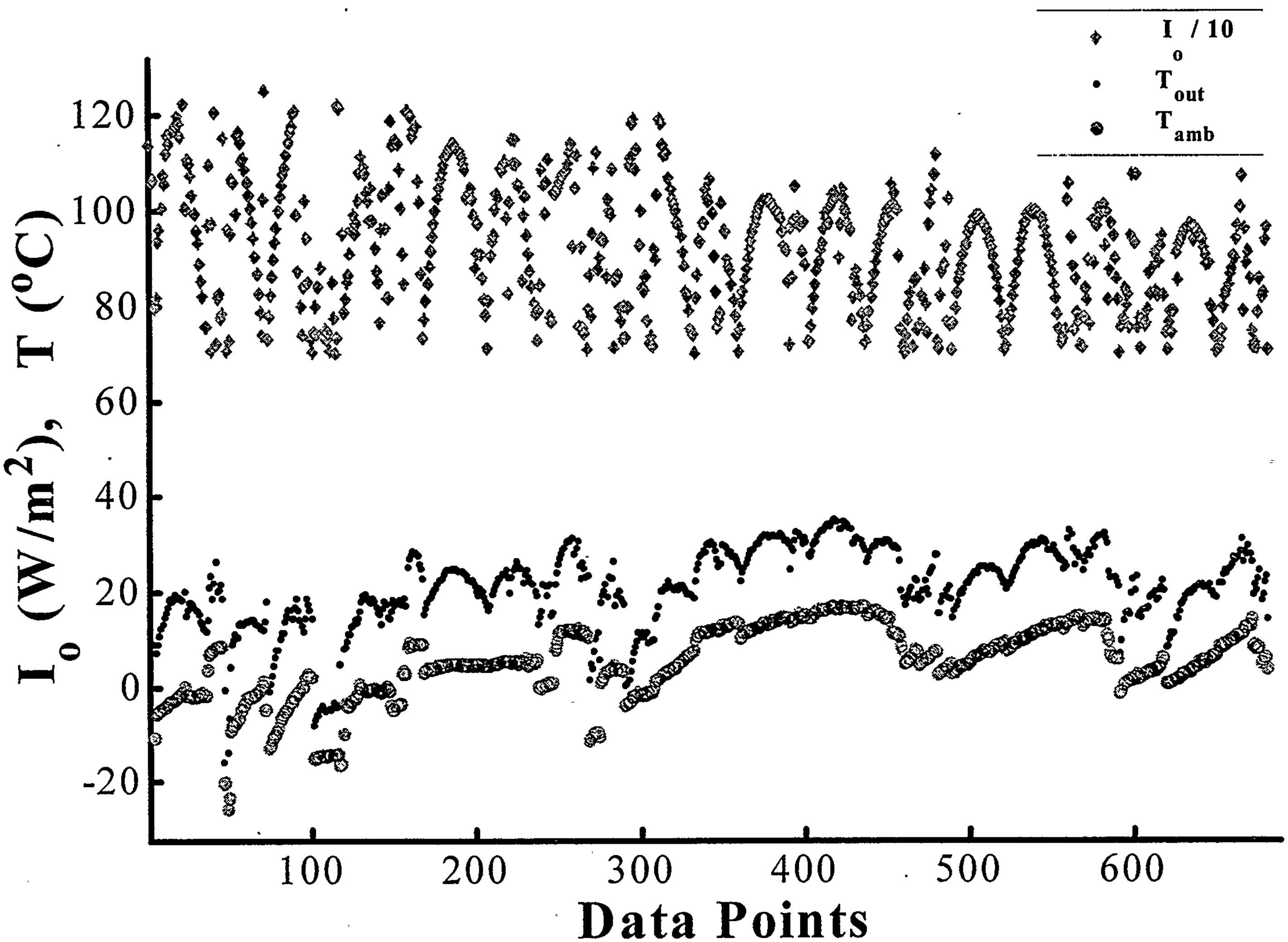


Figure 5.15 Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 700 W/m^2, for airflow rate of 73.78 L/s

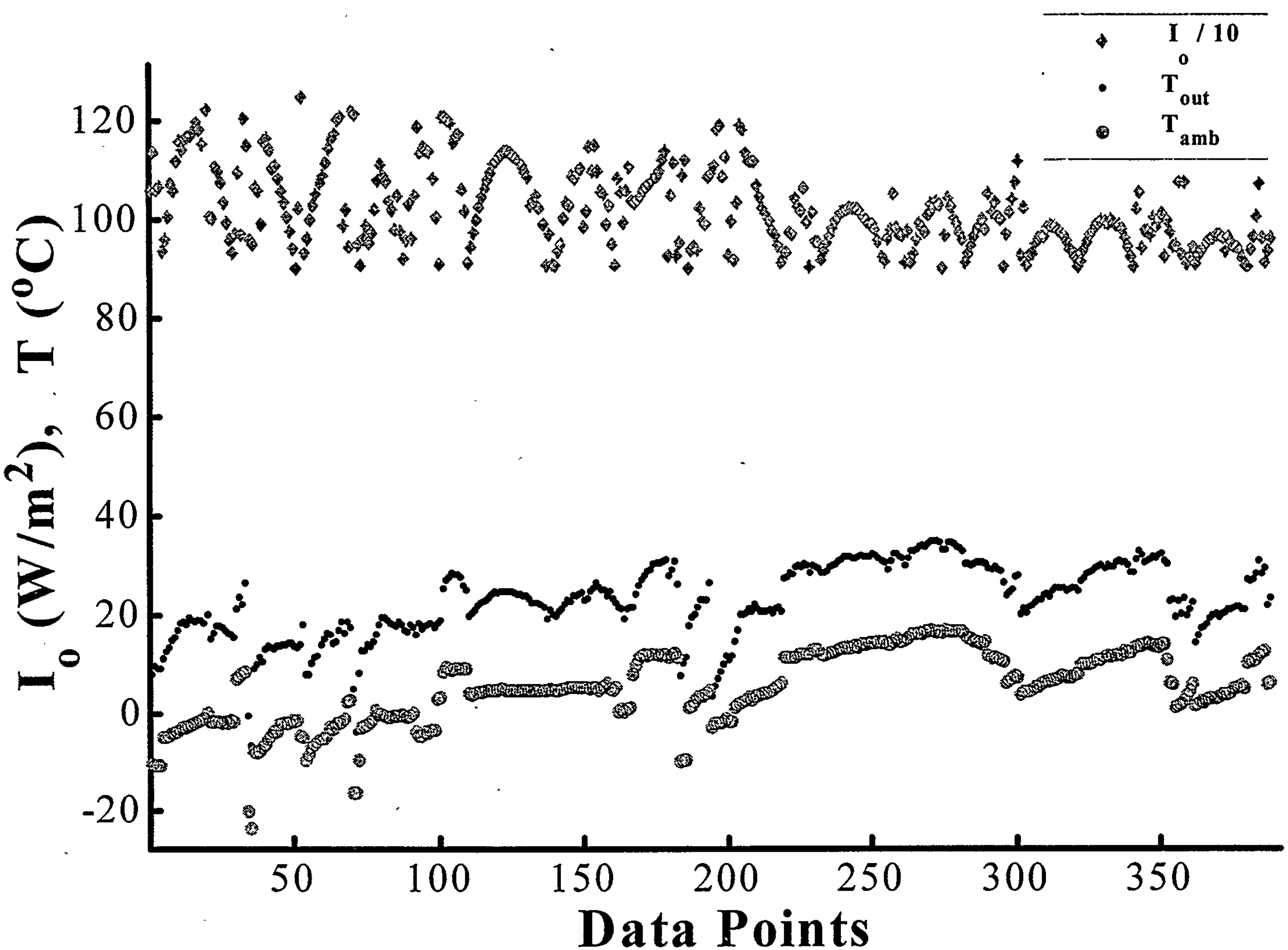


Figure 5.16 Collector Outlet Air Temperature compared to Ambient Air Temperature with Solar Intensity > 900 W/m², for airflow rate of 73.78 L/s

Figures 5.17 – 5.20 show again that there is a strong correlation between the solar intensity and collector outlet air temperature. However, it can also be seen that the outlet temperature fluctuates somewhat less than the solar intensity due to the thermal capacity of the collector. It should also be noted that with the increased airflow rate, more modest temperature gains are achieved; yet a significant air temperature increase is still achieved. **Figure 5.20** shows very consistent midday operation with 20 ^{o}C increases in air temperature. Therefore, achieving the heating requirement that many building air systems would provide for the fresh air intake of the building. With the increased airflow rate to 73.78 L/s the collector is still capable of providing useful air temperatures for buildings.

5.4.2 Efficiency

Figures 5.21 – 5.24 display the efficiency attained by the collector during the 73.78 L/s testing phase. The change in air temperature and efficiency are compared to the solar intensity during the testing from March-May 2002.

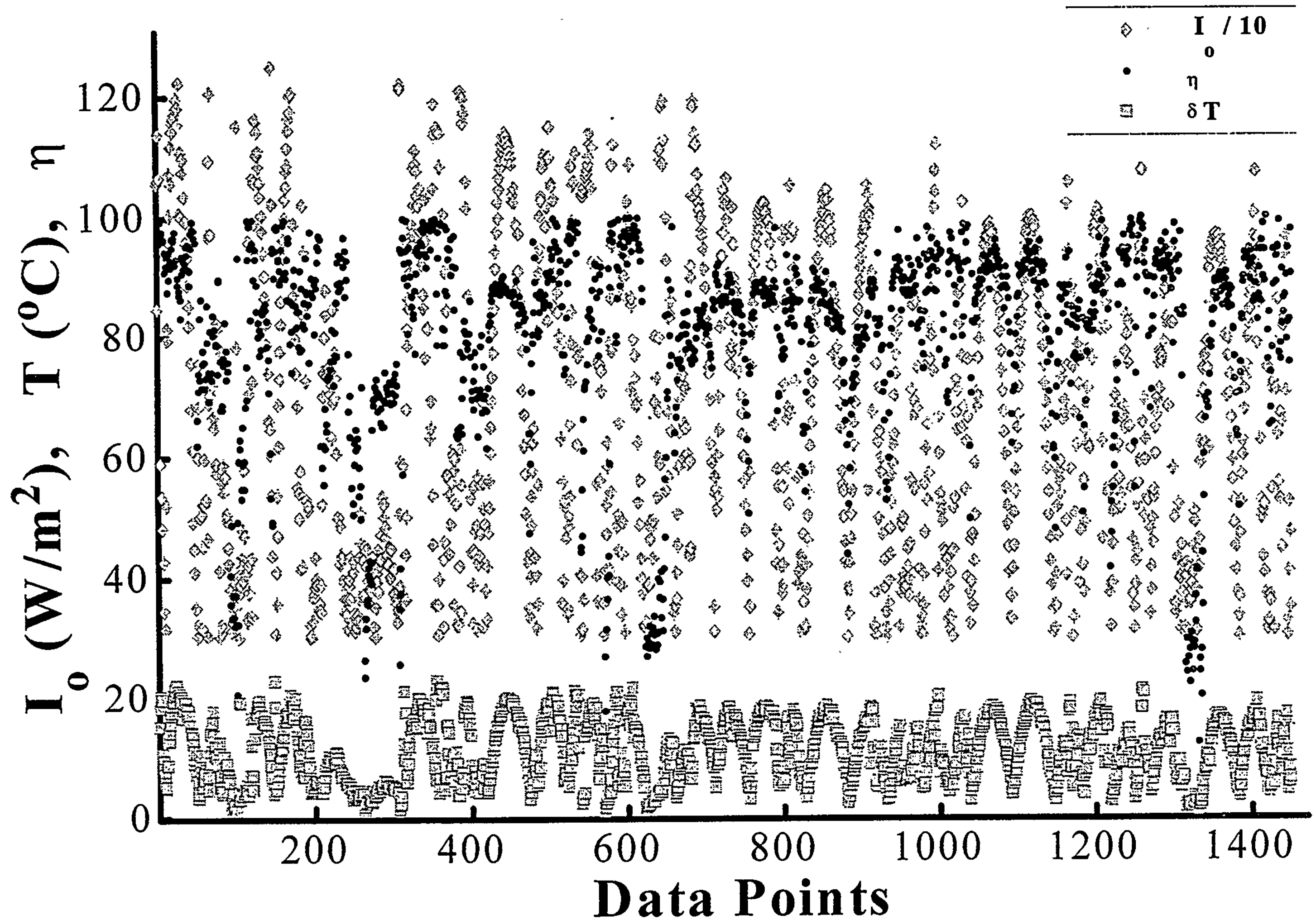


Figure 5.17 Collector Thermal Efficiency with Solar Intensity > 300 W/m^2, for airflow rate of 73.78 L/s

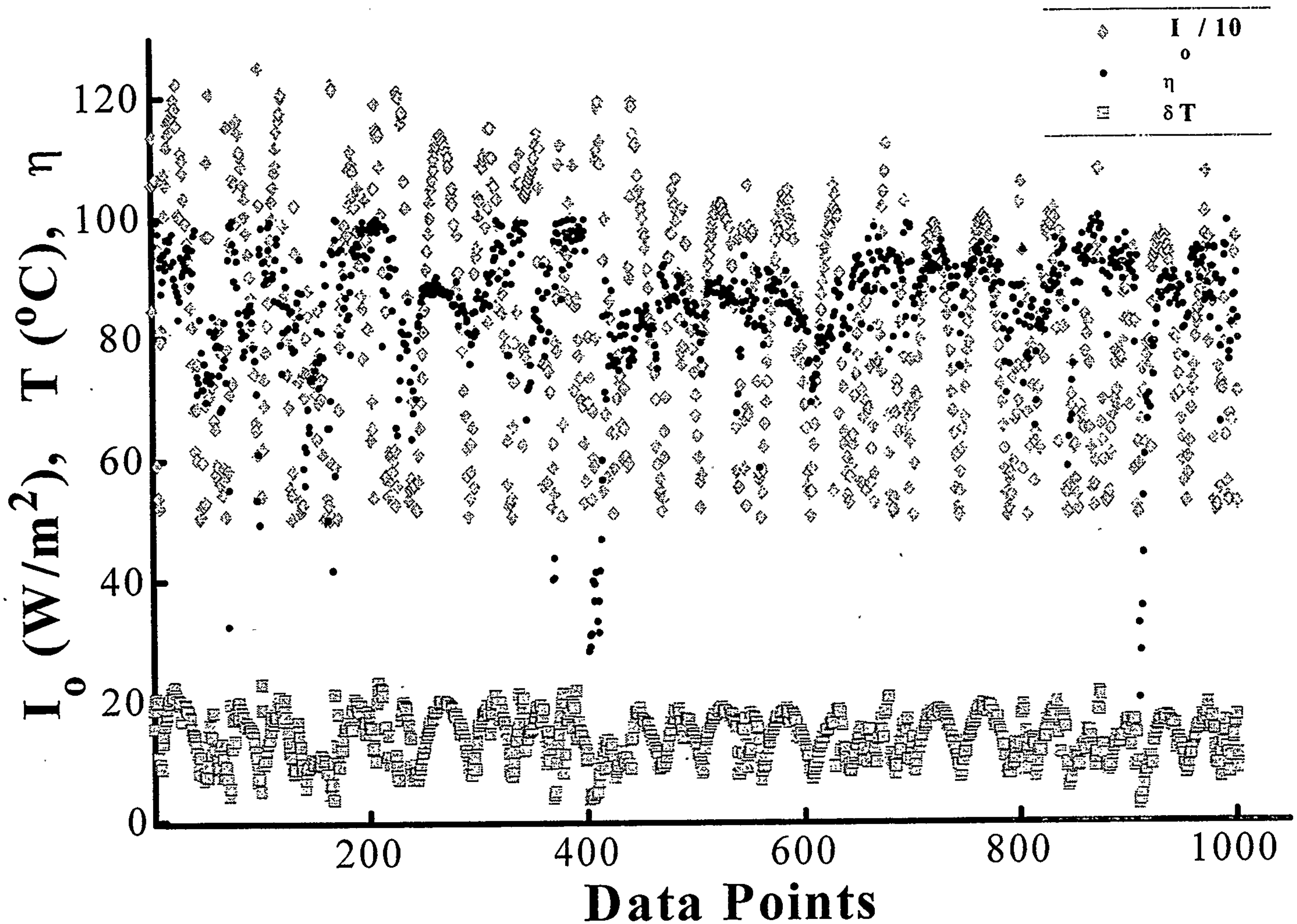


Figure 5.18 Collector Thermal Efficiency with Solar Intensity > 500 W/m^2, for airflow rate of 73.78 L/s

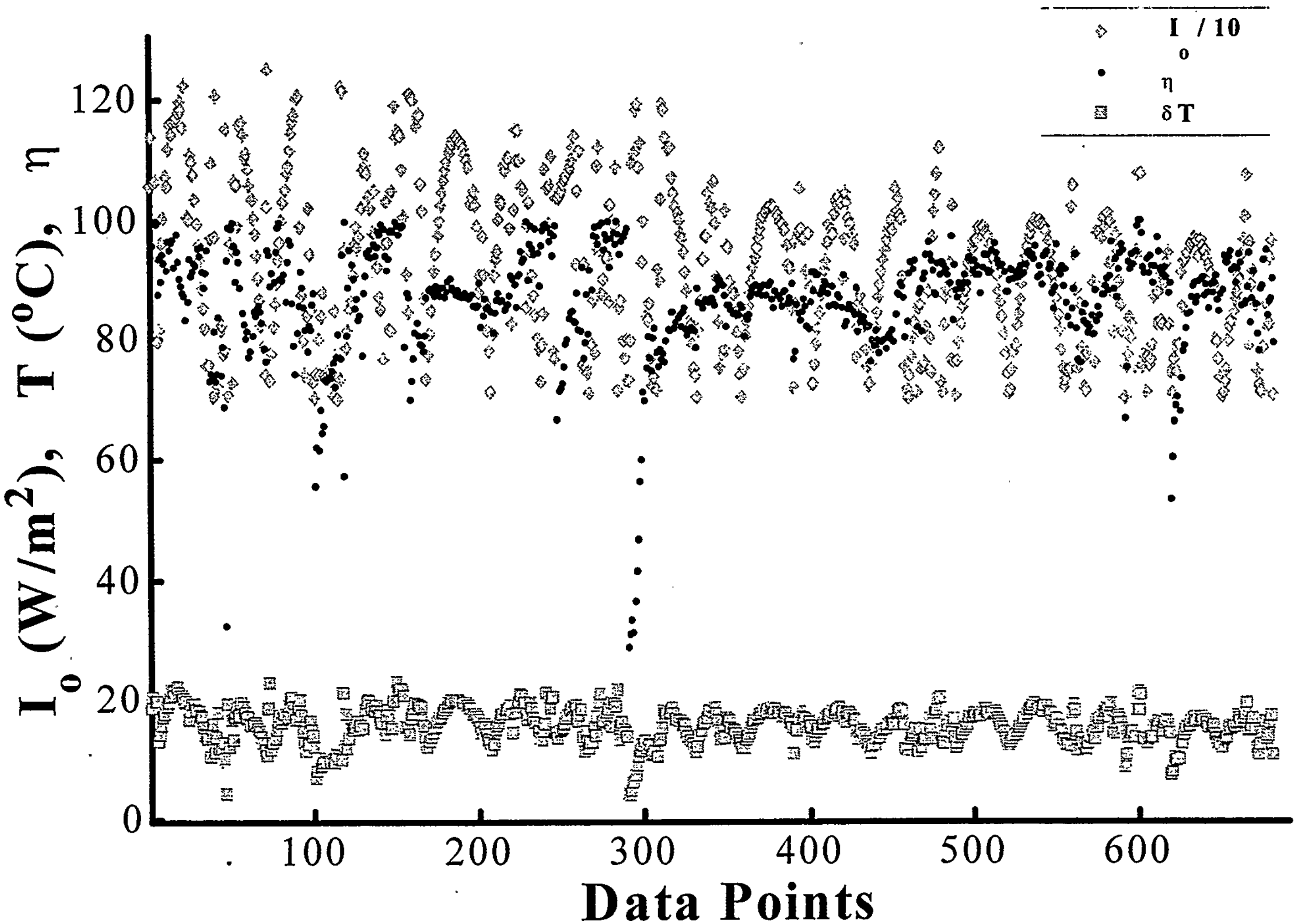


Figure 5.19 Collector Thermal Efficiency with Solar Intensity > 700 W/m^2, for airflow rate of 73.78 L/s

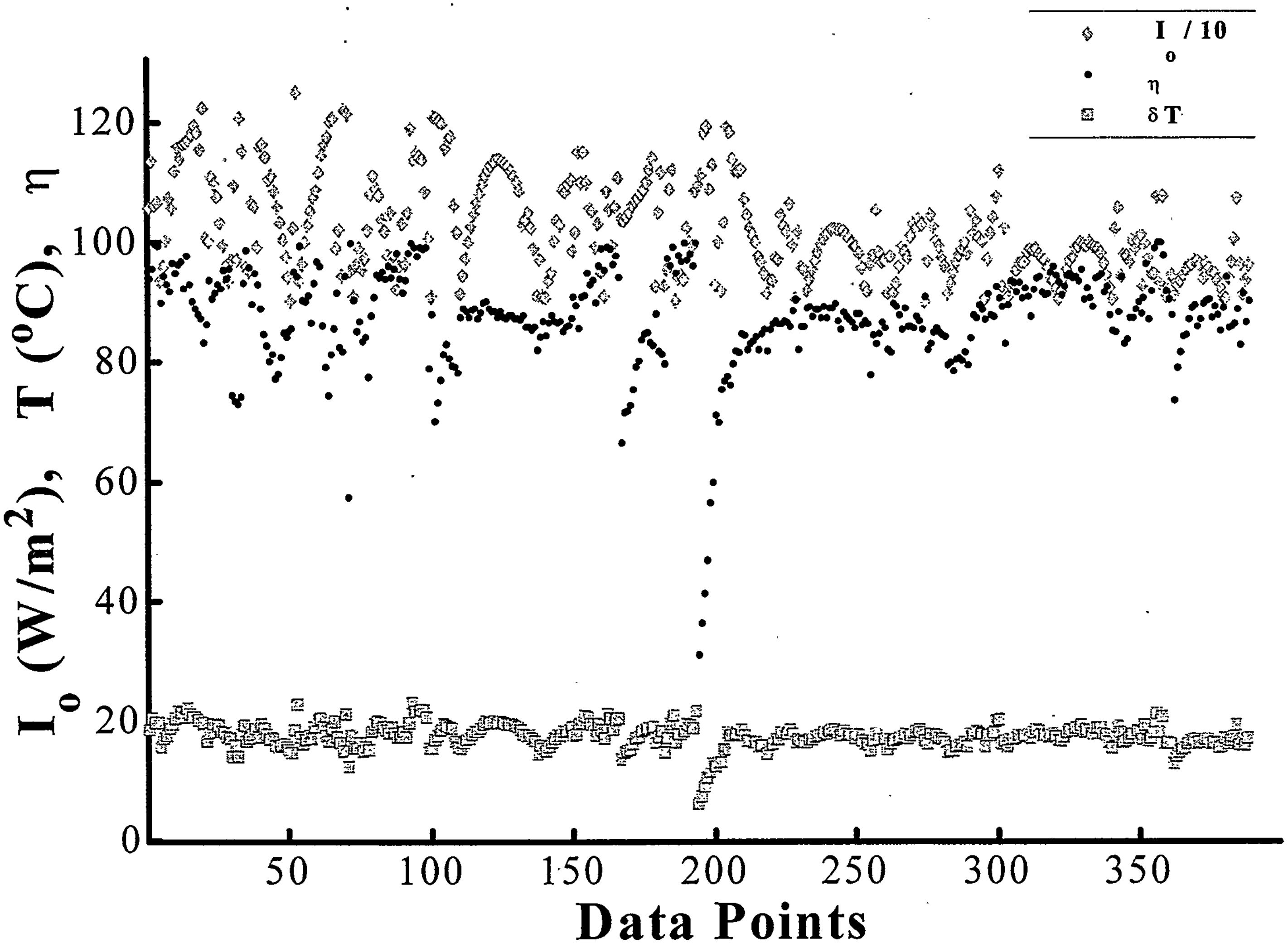


Figure 5.20 Collector Thermal Efficiency with Solar Intensity > 900 W/m², for airflow rate of 73.78 L/s

Again it can be seen that that the collector's performance is consistent under the variety of testing conditions. In general, typical midday temperature gains are approximately 20 °C above the ambient temperature. Some discrepancies in data such as in **Figure 5.20** near data points 190-200 can be explained as a result of snowfall that was not cleaned off in the morning, therefore unrepresentative data was collected. **Table 5.2** shows the overall average efficiency calculated from the collector.

Table 5.2 Average Collector Thermal Efficiency with Airflow of 73.78 L/s

Solar Intensity above, W/m^2	**300**	**500**	**700**	**900**
Average Collector Efficiency	81.0	85.1	86.8	87.4

Table 5.2 shows as the solar intensity raises, the collector efficiency increases. This may seem contrary as increased intensity creates higher temperatures and therefore increased heat loss. However, it is explained by knowing that lower solar intensity again produces more transient system operation. Therefore, the lower intensity values include the transient states of the collector when efficiency would be very low as the collector and absorber are heating up. The collector displays very high efficiencies under a variety of solar intensities, particularly under the higher consistent solar radiation. A comparative analysis will be discussed in the following section.

5.5 Comparative Analysis

In order to confirm the validity of the results obtained, it was chosen to remove sections of the collector in order to reproduce the output results of other conventional collectors. As well, the thermal enhancement of the porous media could be more accurately compared to the conventional collectors by having test data for each collector type with the same airflow rates. Therefore, two further tests were done at each of the previous tested airflow rates; first the top glass cover on the present collector was removed, next the porous bed was removed from the collector. The outer glass cover was removed to quantify the significance of the double air pass with the porous media, at both the 31.21 and 73.78 L/s flow rates. The steel wool bed was then removed to leave the construction of the conventional simple flat plat collector, with one pane of glass, and tested at both of the specified flow rates. Testing was performed for the various configurations, and a day of data will be presented for each of the collectors, at each of the flow rates.

5.5.1 Comparative Data

The data presented for each of the collectors are the efficiency and air temperature increase versus the solar intensity. The data was chosen so that each collector operated during a clear sunny day, which provides an accurate comparison. First, the data with the top glass cover removed, but retaining the porous media, will be presented in the **Figures 5.21** and **5.22.**

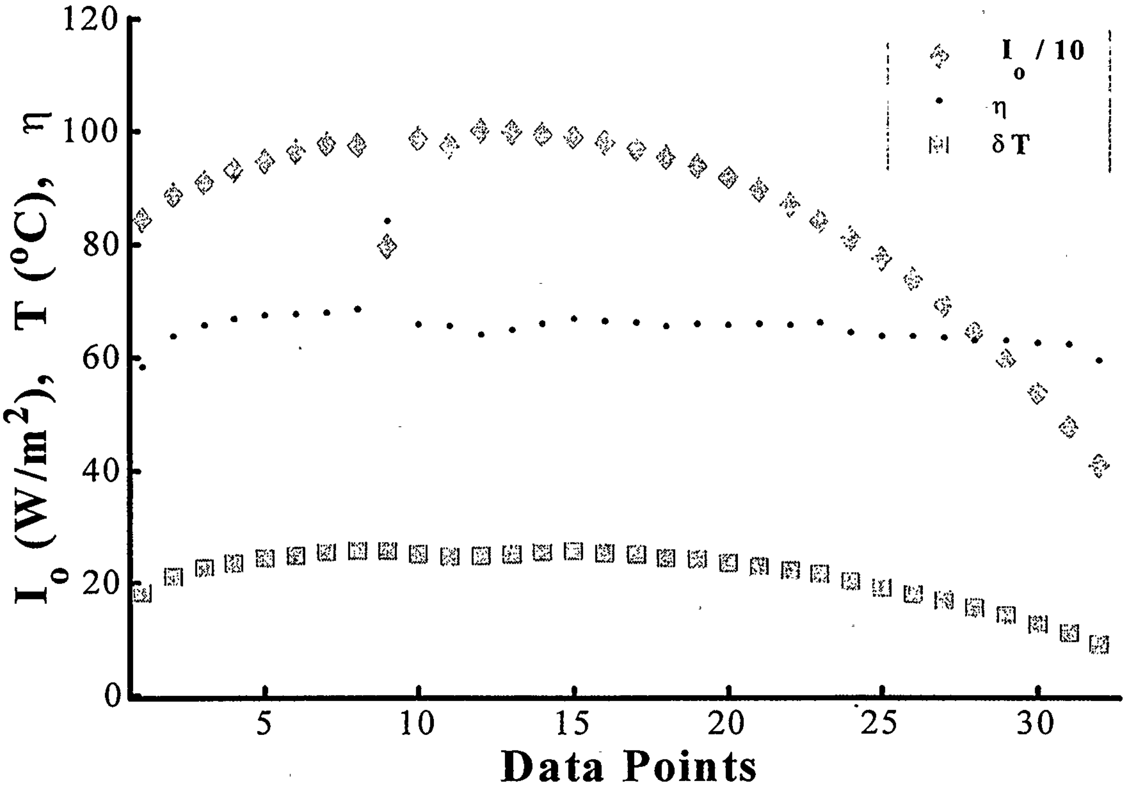


Figure 5.21 Collector Efficiency: One Glass Cover & Porous Media, with airflow rate of 31.21 L/s

The above figure shows a collector with porous media and one glass cover under the lower flow rate condition, producing and average thermal efficiency of approximately 64%. This is in comparison with the two pane/pass collector, which was shown to provide approximately 85% efficient thermal conversion under the same flow rate. Next, the flow rate was increased to the 73.78 L/s condition, for the one cover porous media collector.

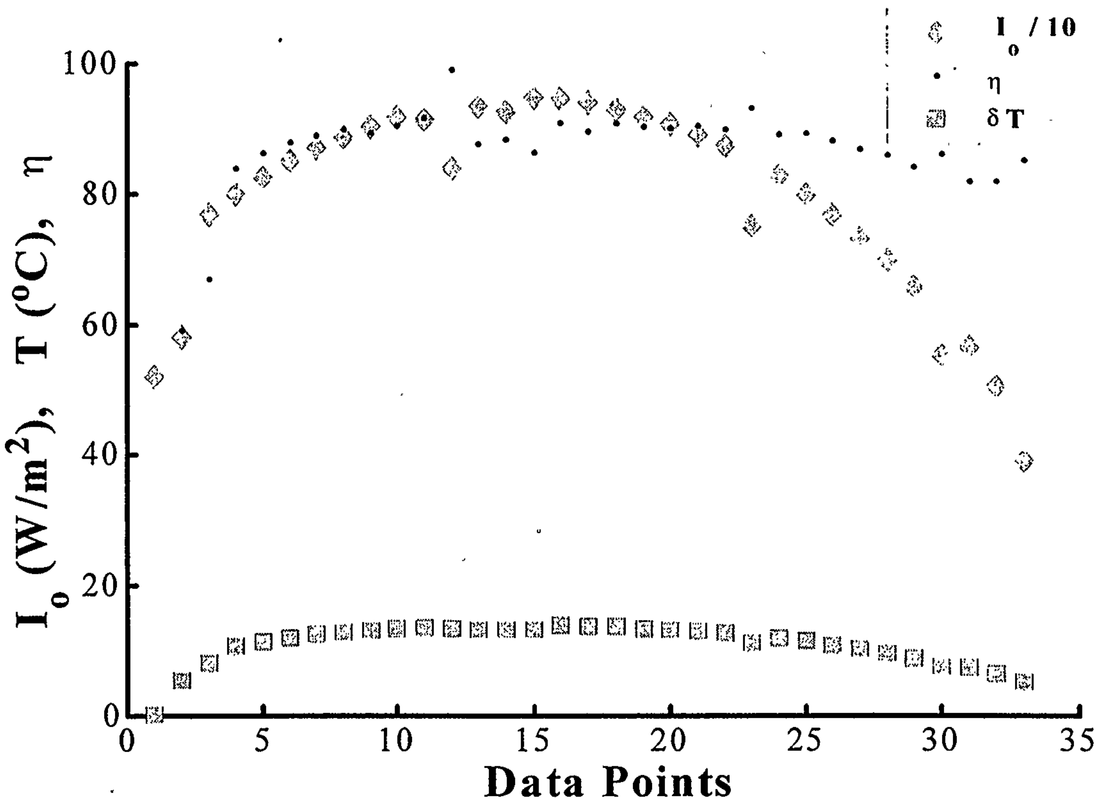


Figure 5.22 Collector Efficiency: One Glass Cover & Porous Media, with airflow rate of 73.78 L/s

At the higher flow rate the one pane/pass collector, and the two pane/pass collector are seen to perform very similarly, both achieving a thermal efficiency of approximately 87% during midday operation. The increased flow rate greatly increased the efficiency of the one cover collector, in contrast to the insignificant effect that occurred in the two pane/pass collector when the flow rate was increased. This is likely resulting from the fact that at the lower flow rate, higher bed temperatures result in a significant amount of heat being lost through the lower glass layer. In the two pane/pass system these losses are recuperated by the first air pass, however in the single pane collector the heat is lost to the ambient.

However, the higher flow rate condition provides a large increase in the heat transfer coefficient through the bed. Therefore, lower bed temperatures occur and less/insignificant amounts of heat are lost through the lower glass cover. This is explained from observing that the two pane/pass collector did not capture a significant amount of heat in the first air pass, as the overall two pass collector efficiency is virtually equal to the single pane/pass collector.

Therefore, it can be concluded that for a porous media solar air heater operating at lower flow rates, 31.21 L/s, a second cover provides a significant increase in the thermal efficiency (approximately 20%). However, for porous collectors operating at higher flow rates, such as the 73.78 L/s, an additional glass cover and air pass provides no significant benefit. Next will be shown the effects of removing the porous bed from the single glazed/pass collector, first at the lower airflow rate.

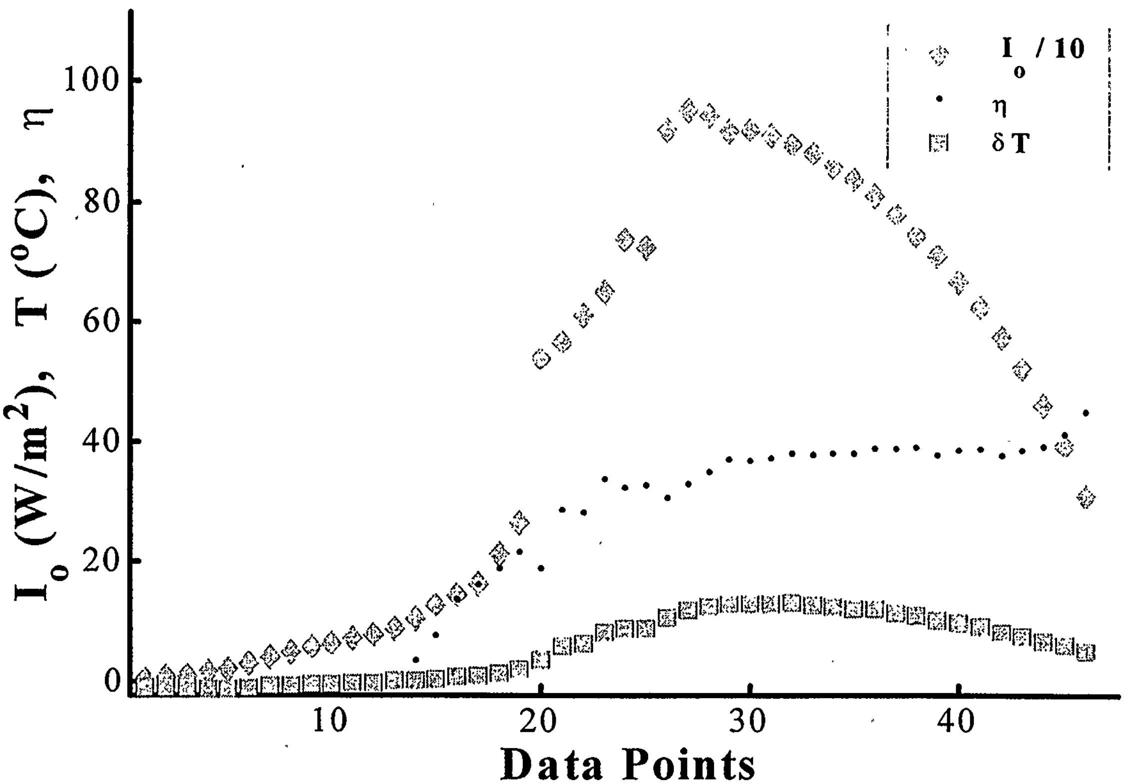


Figure 5.23 Conventional Collector Efficiency: One Glass Cover & No Porous Media, with airflow rate of 31.21 L/s

Figure 5.23 depicts the tested results from a conventional simple flat plate air heater. As discussed the collector proves to have a very low thermal efficiency averaging approximately 35 % with the lower 31.21 L/s airflow rate. This efficiency of the conventional collector is improved significantly by increasing the airflow rate, as can be seen in **Figure 5.24**.

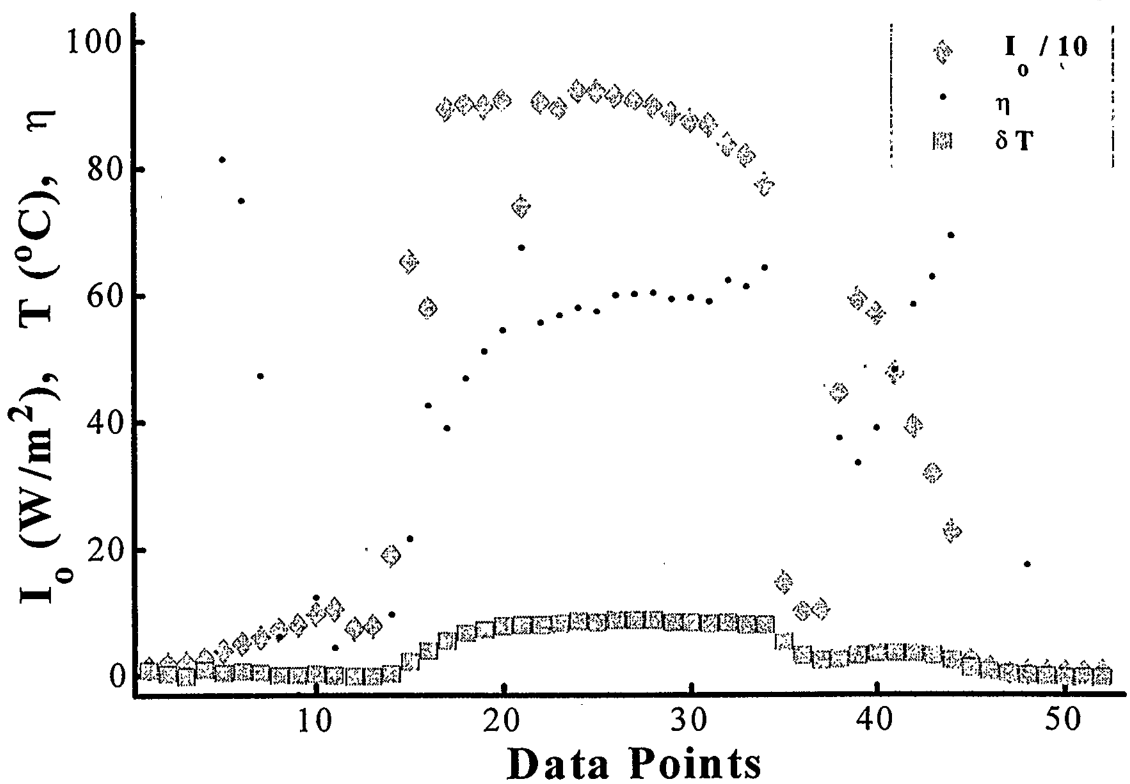


Figure 5.24 Conventional Collector Efficiency: One Glass Cover & No Porous Media, with airflow rate of 73.78 L/s

Figure 5.24 identifies the conventional collector to have an average thermal efficiency of approximately 56 % at the 73.78 L/s flow rate. It can be noted that this is a significant improvement from the lower flow rate efficiency of 35%, however still very poor in comparison with the other tested collectors. **Table 5.3** summarizes the efficiencies obtained from the various collectors tested, as well as the percent improvement in the efficiency that resulted from the thermal enhancement methods.

Table 5.3 Comparative Analysis of Various Collectors' Thermal Efficiency

	Thermal Efficiency of Compared Solar Collectors				
Airflow	**Conventional Flat Plate**	**One Pass & Porous Media**	*% Thermal Enhancement**	**Two Pass & Porous Media**	*% Thermal Enhancement**
31.21 L/s	**35%**	**64%**	*82%*	**85%**	*140%*
73.78 L/s	**55%**	**85%**	*54%*	**87%**	*58%*

(* *Thermal enhancement based on conventional collector performance*)

Table 5.3 identifies the significant thermal enhancement that porous media is able to accomplish in solar air heaters. The higher flow rate conditions are found to have a significant effect in improving the efficiency by almost 60%, but are yet modest improvements when considering the increases at the lower flow rates. Due to the lack of turbulence in the conventional smooth collector, porous media is able to drastically improve the heating potential of a collector, up to 140% for the lower flow rates. The following section, discussing the performance of the collector, will further emphasize the significant effect of porous media and the two-pass system.

5.5.2 Performance Curves

A common way to compare solar collectors is by plotting *performance curves* for the collectors. Performance curves are created by plotting the efficiency of the collector versus the air temperature increase divided by the solar intensity, at various airflow rates.

Each point is plotted based on, $\frac{(T_{out} - T_{amb})}{I_o}$, and η.

The performance curve is usually used to measure the effectiveness of collectors at different flow rate conditions. These curves identify the ability of a collector to maintain a high efficiency under a variety of air temperature increases. As discussed earlier, higher efficiencies are not uncommon for collectors operating with low temperature increases, and a high flow rate environment. However, efficiency values typically decline rapidly as the flow rate decreases, and the temperature gradient increases. On a performance curve, a more horizontal plot refers to a collector that maintains a similar efficiency for a variety of airflow and solar intensity conditions. A plot that declines rapidly refers to a collector that has a varying efficiency, dependant on the operating conditions, which is a less desirable characteristic for obvious reasons. **Figure 5.25** displays the performance curves for the collectors tested in this section. These results are consistent with the theoretical analysis of Mohamad (1997).

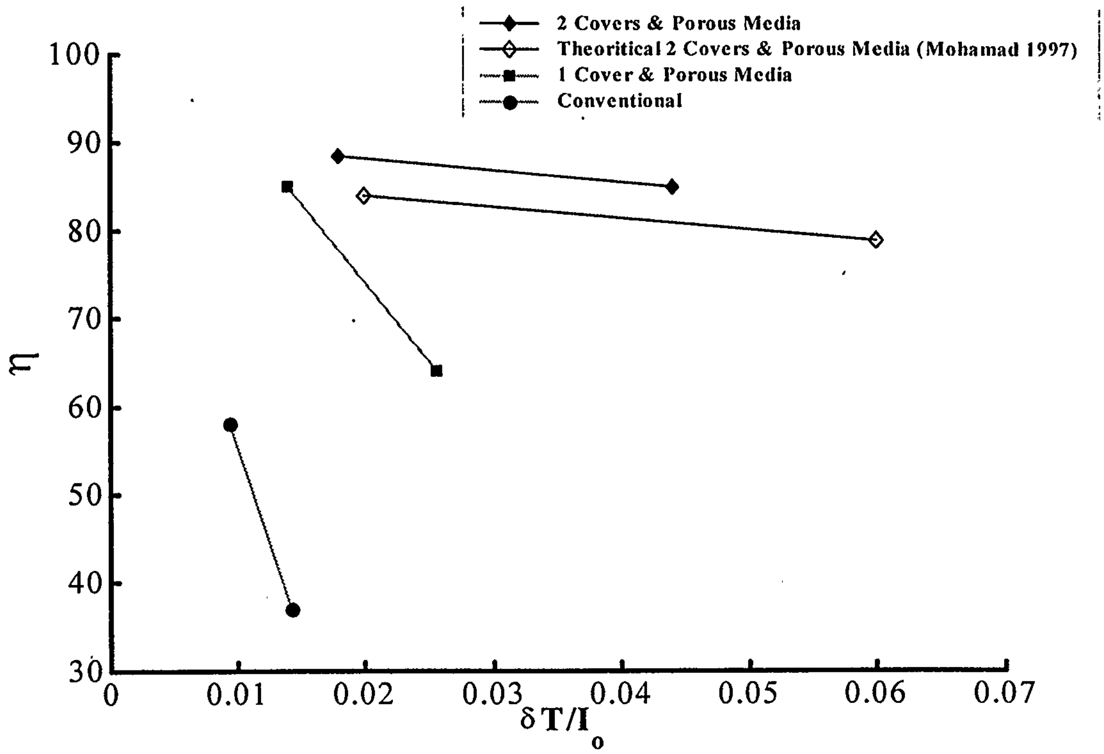


Figure 5.25 Performance Curves of Collectors Discussed

Figure 5.25 clearly shows that the performance of the present solar air heater, with porous media and a two-pass system, provides drastically improved operating capabilities. Whereas the characteristic of the conventional collector is to drop in efficiency significantly as the flow rate decreases (i.e. temperature gradient increases), the present collector has shown to maintain a high thermal efficiency in a variety of operating conditions. The porous media provides superior thermal output from the collector. It is also necessary to consider the other effect of the porous bed being the pressure drop, which the next section will discuss.

5.6 Pressure Drop

The increase in turbulence of the porous media adds to the thermal performance of the system, however, it also increases the pressure drop in the system. Pressure drop increases the fan power required for the system, and therefore is desired to be minimized. Therefore, it was necessary to quantify the pressure drop incurred by the addition of the porous bed to the solar air heater.

It was found that at the higher flow rate of 73.78 L/s, a 0.020 kPa differential pressure was determined between the collector and the ambient. This value is acceptable and within the limitations of fan power required for a collector. Pressure drop from the lower flow rate was very small at only 0.005 kPa. These values are quite acceptable for solar air heating applications. The very low pressure drop is due to two main considerations. Firstly, the porosity of the bed is very high, approximately 99%. Second, the porous layer does not fully occupy the duct between the lower glass and bottom of collector, (a border of 2.5 cm was left open in all directions surrounding the suspended porous bed).

The porosity of porous media used in the collector does not present practical limitations on the use of the media for solar air heating, concerning the pressure drop that is incurred. The drastic improvement in the thermal output and efficiency of the collector is more than justified for the less overall significant increased pressure drop.

This concludes the presentation of data collected for the solar air heater. Finally some concluding statements and recommendations for future work will be discussed in the next section.

CHAPTER SIX: Conclusion & Recommendations

6.1 Conclusion

Solar air heating is already established as a viable alternative to fossil fuel space heating for many applications such as fruit drying, crop drying, green house heating, space heating etc (Hachemi 1998, Sharma 1994). Solar heating has potential to provide a significant fraction of the space-heating requirement for Canadian buildings. Current solar heating technology has limited the economic viability of solar heating for some applications. Conventional solar air heating collectors operate with efficiencies between 40-50%. The present solar collector has shown to operate with an average efficiency of 84% and 86% for airflow rates of 31.21 L/s and 73.78 L/s, respectively. The system is able to achieve temperature increases of up to 50 °C for the lower airflow rate tested.

The collector has proven a most successful technique for increasing the heat transfer mechanism between the airflow and the absorber. The collector has shown to lower temperature differential between the absorber and airflow stream, thereby reducing the heat losses from the absorber plate. Operating with the higher flow rate, and producing a 20 C airflow temperature increase, the collector is able to keep the temperature differential between the absorber and air stream to less than 5 degrees **(Fig. 5.2)**.

The performance of the tested collector is superior to the conventional and modified collectors previously investigated by others. The present collector has extremely high thermal efficiencies under a variety of operating conditions tested. The performance of the collector is a significant improvement to the conventional solar air heating technology currently available. The collector has potential to utilize solar energy to heat homes and buildings efficiently and economically.

6.2 Future Work

This study has shown the increased potential of solar air heating via the use of porous material and a two-air pass collector. In order to further the work in providing a viable space-heating alternative to the public, there are a number of considerations to address for the successful design and integration of the collector into the public. Some of the issues to be addressed are:

- Practical considerations
    - Snowfall, ice, dust, debris removal for a roof top installation
    - A design/material usage increasing the manufacturability of the collector
        - Solar powered variable speed fan
- Consider integration with earth tube/heat pump and storing heat in the ground during the summer
- Operate system by re-circulating warm indoor air through the collector to simulate re-circulation and reheating of indoor air through the collector
- Test system with different glazing materials

- Test system by changing altitude orientation every 2 weeks etc
    - Compare winter gains with constant angle operation
- Test system with varying airflow rate so as to achieve higher air outlet temperatures
    - Operation of the system with various constant temperature output requirements, more suitable for heat storage
- Integration of a economic heat storage facility with the system

Storage of the solar thermal energy remains to be a very nontrivial and significant problem to the successful integration of solar heating systems. Researching in the thermal storage area, as well as the previous mentioned areas would increase solar air heating feasibility in many applications. Retaining the large quantity of heat captured during midday operation, when often the heat isn't required at that time, would significantly add to a practical solar heating system.

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