PROVISION OF POINT-SOURCE WATER BY ENCHANCED SOLAR DISTILLATION

Report to the

Water Research Commission

by

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WRC Project No 468-1-94

February 1994

ISBN 1 86845 094 5

1. INTRODUCTION

The use of a solar membrane distillation unit to provide potable water in areas where there is a lack of a reliable source of such water has certain advantages over conventional desalination technology. This is particularly true in cases where the affected areas are remote and the demand for potable water is so low that the economy of scale is correspondingly low. If, in addition, the solar distillation unit is portable (a property lacking in conventional solar stills) this could be considered an advantage over conventional desalination and water purification techniques.

In general, the aim of this research project was to design and create a portable solar membrane distillation unit, constructed with inexpensive plastic components. Such a unit was envisaged to (i) be simple to operate, and (ii) require low maintenance costs.

2. OBJECTIVES

The specific objectives of the study can be summarized as follows:

1. To prove the capability of constructing a foldable, storable, membrane-distillation bag which can be used in emergencies to meet daily requirements of sterile and desalinated water, and a unit to produce 1-10 ℓ of such water per day by the use of solar heat, body heat, heat from hot rocks or cooling by wind.

2. To indicate the constructability of a movable membrane air-gap distillation unit operated by solar heat and air-cooling which can be used on farms to desalinate brack borehole water in quantities of 100 ℓ or more per day.

4. To develop the appropriate theory behind the system in order to describe the interaction of the various heat- and mass-transfer processes involved.

5. To design and optimize the unit by computer simulation developed from the above-mentioned mathematical model.

6. To produce prototype stills which will be used to evaluate the validity of the computer simulation models.

7. To collaborate in international joint programmes in this development in order to enhance the effectiveness of the final device, and to publish and/or patent it.

3. BASIC PRINCIPLES

The basic principles of Membrane Distillation, Solar Distillation and Evaporative Cooling are discussed in more detail in the main part of the report. In simple terms, the process of membrane distillation is one whereby water vapor from a heated solution passes through a microporous membrane and is condensed on a cooling surface, and the condensate of high purity is collected. The microporous membrane should be hydrophobic to prevent passage of the formed condensate through the membrane, while allowing water vapor from the heated solution to pass through.

4. PROPOSED DISTILLATION UNITS

4.1 SINGLE-EFFECT UNIT

The basis of the design is shown in Fig. 4.1. A clear plastic sheet is supported over a black radiation-absorbing membrane bag. This bag rests on a condensing surface, from which it is separated by a thin highly porous spacing material. Sunlight enters through the front sheet and is absorbed on the membrane bag which in turn heats the water. Water evaporates from the front and the rear of the bag and runs down the plastic surfaces to a collection point.

An evaporative cooling bag is placed at the back of the unit and is used to extract heat to the rear, and thus increase the production rate, as will be explained in the Section 4. The evaporative cooler is made of canvas, which contributes to the low cost of the system.

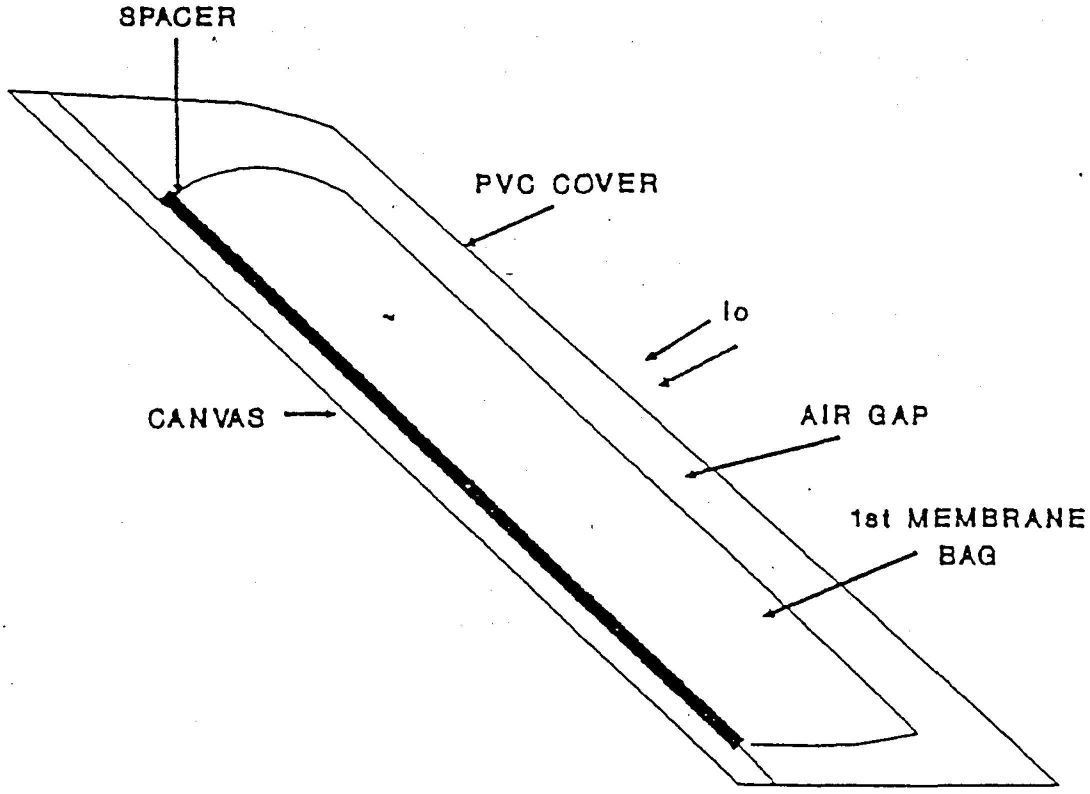

Figure 4.1 : Single-effect unit.

A preheater (Fig. 4.2) is used to preheat the entering water to around 50°C. Again the design of the preheater follows the basic concept of solar collection by the use of black absorbing PVC as the base. A clear PVC sheet is welded above the black PVC to form channels for the water. A clear plastic sheet is supported over the bag itself to reduce heat losses to the environment. Solar radiation passes through the front and second covers and is absorbed by the black PVC. This input of energy causes the water in the channels to be heated.

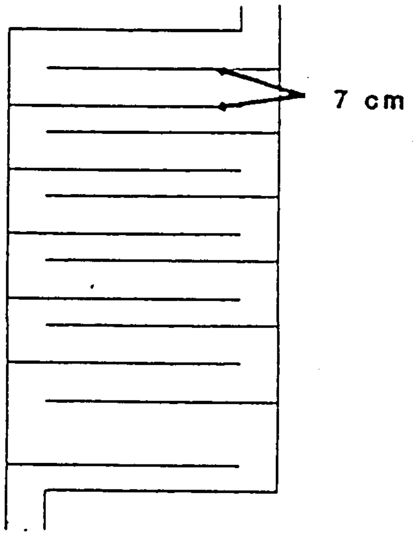

Figure 4.2 : Preheater.

All of the above-mentioned units will be placed at an optimum solar-incidence angle and will face north.

4.2 DOUBLE-EFFECT UNIT

The economics of many distillation processes can be improved by re-using energy. In multiple-effect evaporation systems, for example, this is achieved by using the vapor produced in one stage to supply energy to the next stage. This is the main idea behind the alternative unit in which a double-effect system is used (Fig. 4.3).

It is easy to see that the inclusion of another membrane bag between the first one and the evaporative cooler makes the re-use of energy possible from the front to the rear of the unit. The heat from the first bag will pass through the plastic and heat the water in the second bag. This water will then evaporate to produce more pure distillate.

The evaporative cooler plays an important part in this unit since it ensures the transfer of heat from the front of the unit to the back, and thus increases the re-use efficiency.

This system will also be coupled to the same preheater.

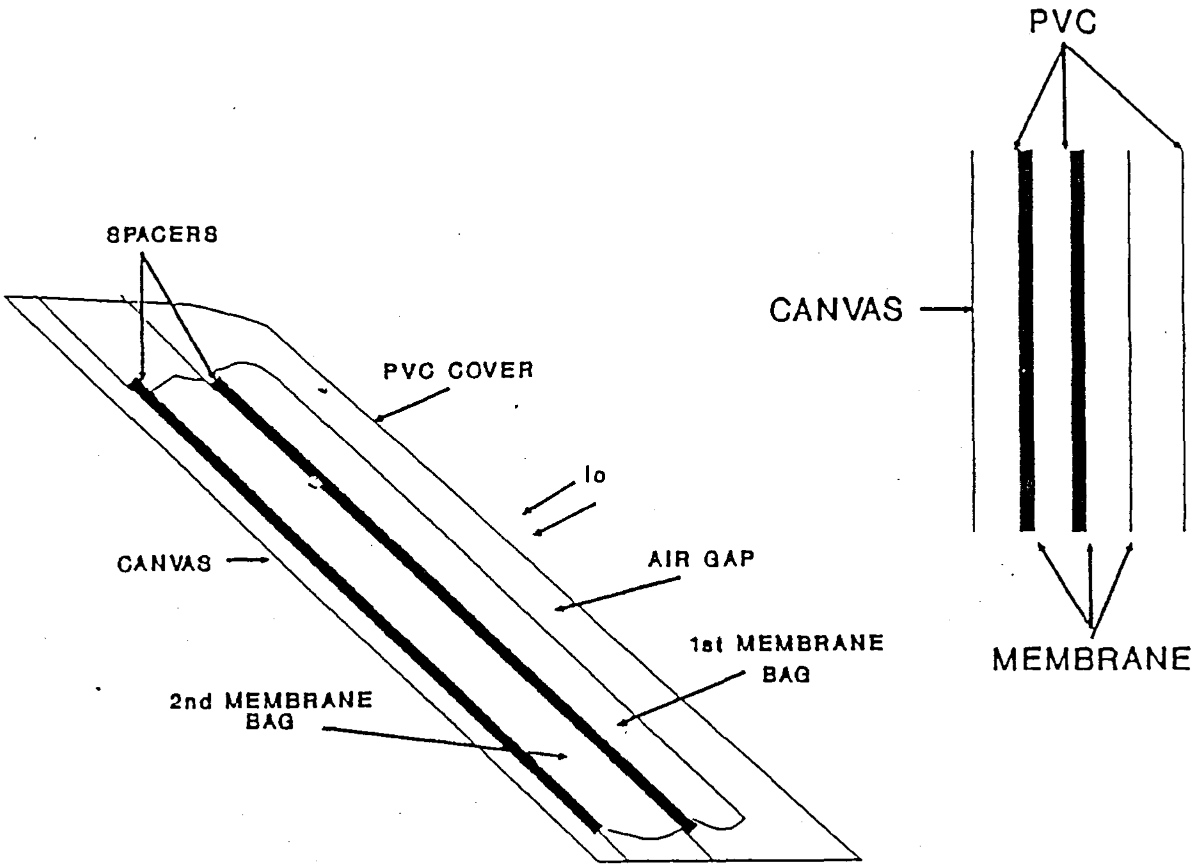

Figure 4.3 : Double-effect unit.

5. EXPERIMENTAL WORK

A thorough literature survey on the subject was conducted. The relevant equations for describing heat- and mass transfer in the membrane distillation process were obtained, and used to create a computer simulation model for (i) a single-effect unit with cooling and a preheater, and (ii) a double-effect unit with cooling and preheater.

Computer simulations were done for the preheater, and for both the single-effect and double-effect units. For the preheater, simulations were done on the effect of a variety of variables on the water temperature in the preheater. For both the single-effect and double-effect units the effect of (i) environmental conditions and (ii) design variables on the production rate of the respective units were simulated by means of the models developed.

Results thus obtained for the single- and double effect units were compared. A simple experimental unit (single-effect) was constructed and experiments carried out in the laboratory. The results thus obtained were compared with the results from the computer simulation.

Subsequently, further experimental work was carried out when it became clear that the concept of a heated membrane bag was not workable.

Canvas was used to make the membrane bag for the first experimental model. This was, however, not satisfactory because the canvas was not strong enough to withstand the pressure from the water inside the bag. The idea of heating a membrane bag, with production on both the front and the back sides of the bag, was abandoned because an exceptionally strong material would be required to withstand the direct sunlight.

A second experimental model was built, using an anodized aluminium plate to absorb the solar heat. The water was placed between the plate and the membrane, to allow the water to be heated by the plate. Experiments carried out in direct sunlight showed that the temperature of the black aluminium plate rose to above 80°C. Although this experiment was carried out in direct sunlight, there was also a great deal of heating by radiation, so that it would be possible to operate the distillation unit on cloudy days.

A variety of problems, with leakage being one of the most serious, made it necessary to build a third model. The third model had the advantage that different membranes could be tested without the need to build a new model for each new membrane, as was the case with the previous models.

Although this third model modelled only a single effect, it produced helpful test results. The heating of the water by sunlight was simulated by means of a heating element in the laboratory. Two pumps were used to circulate the heated water, as well as the cooling water which was necessary to keep the condensing surface at a specified temperature.

6. RESULTS AND DISCUSSION

6.1 COMPUTER SIMULATION SENSITIVITY STUDY

6.1.1 PREHEATER

The preheater outlet temperature varied from 40 to 60°C, depending on the different environmental and design conditions, which resulted in a temperature difference of 20 to 40°C/m^2 of preheater surface. The flow rate through the bag was doubled to 10 ℓ/h which resulted in an outlet water temperature of 43°C compared to an outlet temperature of 58°C when a flow rate of 5 ℓ/h was used.

6.1.2 DISTILLATION UNIT

6.1.2.1 Single-effect unit

Higher production was obtained with high solar radiation input levels. The production through the diffusion gap behind the membrane bag was also noticeably higher than that through the air gap in front of it. A rise in ambient temperature produced a slight rise in production. This was a result of the increased proportion of heat transferred by vapor at higher temperatures.

The windspeed had a relatively minor effect on the productivity of the unit. Again, this was because the windspeed did not affect the energy input to the system. A low windspeed implied a low external coefficient of heat-transfer between the unit surface and the environment. To maintain the rate of heat transfer at low windspeeds the temperature of the unit surface had to be increased. This increased the temperature throughout the unit, which was favorable for distillation.

The humidity had initially no effect on the total production by the system, although a slight increase in front production and a decrease in back production was noticeable. This was because the evaporative cooling was less effective at higher humidities which resulted in more heat being available for evaporation in the front and less at the back.

One of the most important design variables in the design of a solar distillation system, is the total reflectance of the system. There was a steep decrease in production as the total reflectance increased. Materials of construction, as well as various solar incidence angles, are important in minimizing the total reflectance of the unit.

The size of the gap between the membrane bag and the condensing surface in the rear section also played a role in the design of the bag. A larger diffusion gap resulted in a lower total production rate. This was because the larger diffusion gap increased the resistance to heat transfer in the rear of the unit. It is, however, interesting to note that the front production increased because more heat was available for production in the front.

Varying the front gap size had little or no effect in productivity. This illustrated one of the most important differences between the heat transfer at the front and at the rear of the unit. Whereas in the rear section vapor and conducted heat diffuse across an air gap, in the front this process is by free convection. With conduction terms the resistance varies linearly with the distance. In free convection, however, the resistance term is dependent on the temperature difference and the dimensions of the cavity. Over the practical range of interest it was apparent that these effects cancelled each other out.

6.1.2.2 Double-effect unit

The same trends were apparent with this unit than discussed with the single-effect unit.

The double-effect unit gave a much higher production than the single-effect unit (60%) did. This was because heat was re-used for evaporation at an extra surface. Theoretically it should be possible to have a triple-effect or higher but construction difficulties would make this very difficult.

The simulation was also done with a flow rate of 10 ℓ/h rather than the standard value of 5 ℓ/h. The only difference was a slight decrease in the production rate [from 0,671 kg/(h.m^2) to 0,656 kg/(h.m^2)]. This was because the operating temperature of the unit was slightly lower because of the lower temperatures of the inlet water entering the unit from the preheater.

6.2 EXPERIMENTAL UNIT

The results obtained from the experimental unit, at steady state, are compared with those of the computer simulation:

Table 1 : Comparison of results from experimental unit and computer simulation.

WATER TEMP (°C)	EXP. PRODUCT [kg/(h.m2)]	SIM. PRODUCT [kg/(h.m2)]
45	0,272	0,175
50	0,312	0,264
55	0,348	0,292

Because of experimental difficulties concerning the membrane bag, these were the only results that could be obtained. The experimental production rates were higher than those obtained in the simulation. A possible explanation could be that there was a greater difference between the temperatures of the water inside the bag and the outside condensing surface, which created a higher evaporation driving force in the front cavity. This was because solar radiation was not absorbed by the clear cover, which in turn created the greater difference between the temperature of the outside unit and the indoor unit. It should be noted that there was, at this stage, a considerable difference between the experimental unit and the simulated unit and for this reason no final conclusions can be drawn as to how closely the two models compare.

6.3 FURTHER EXPERIMENTAL WORK

The preliminary tests yielded some results on the rate of production of potable water as a function of the temperature of the heated water, as well as of the cooling water.

Two types of membrane were tested, one with a material cloth on both sides of it to protect it, and the other with cloth on only one side of it.

In the first experiment the cooling-water temperature was kept constant at 14°C, and the temperature of the heated water was varied. This experiment was conducted using the membrane with cloth on both sides of it.

Table 2 : Membrane 1 : Cooling-water temperature constant (14°C).

HEATED-WATER TEMP. (°C)	PRODUCTION RATE [mℓ/(h.m2)]
50	74,1
54	78,0
60	160,7
62	183,5
65	192,7
76	330,3

For the second experiment the influence of the cooling water temperature (condensing surface) was investigated, with the temperature of the heated water being kept constant at 65°C.

Table 3 : Membrane 1 : Heated-water temperature constant (65°C).

COOLING-WATER TEMP (°C)	PRODUCTION RATE [mℓ/(h.m2)]
13	204,5
15	192,7
19	183,5

The second membrane (with protecting cloth on only one side) was tested to determine whether the cloth had any influence on the rate of diffusion of vapor through the membrane. The temperature of the cooling water (and thus of the condensing surface) was also kept constant at 14°C.

Table 4 : Membrane 2 : Cooling-water temperature constant (14°C).

HEATED-WATER TEMP. (°C)	PRODUCTION RATE [mℓ/(h.m2)]
48	517,1
57	587,2
61	652,4
64	764,3

In conducting these tests with the membrane with cloth on only one side of it, a 2 000 ppm sodium chloride (NaCl) solution was used to ensure that there were no leakages in the membrane. The concentration of NaCl in the permeate, varied from 250 to 400 ppm sodium chloride. The retention of NaCl was about 85%, but in some cases it was as high as 90%.

The influence of the cooling-water temperature on the permeate production rate was tested in one experiment in which the temperature of the cooling water was kept constant at 40°C. With the temperature of the heated water 65°C, the permeate rate was 0,876 $\ell/(h.m^2)$. This higher production rate at a higher cooling water temperature can be very useful when a model which consists of more than one stage, is built. This higher cooling-water temperature can be used for a second stage, where the production rate may be small, but can favorably influence the production rate in the first stage of the solar distillation unit.

6.3.1 DISCUSSION OF RESULTS

The above results show that the protecting cloth has a definite influence on the diffusion rate of this vapor to the condensing plate. Ideally, it would be best to use a membrane without a cloth, but the membrane would be damaged too easily, which would result in leakages of non-potable water onto the condensing surface. The "Teflon" membrane with cloth proved to be the best option, because reasonable protection of the membrane could be obtained and a high rate of production of potable water was achieved.

The results confirm the idea that the temperature of the heated water has a very important influence on the permeation rate. On thermodynamic grounds the amount of vapor that is formed would increase if the temperature of the heated water was increased.

The temperature at which condensation occurs does not play an important role in the amount of permeate formed. It may be an important variable when more than one stage is built into the test model.

One of the factors which influences the permeate production rate considerably, but which cannot be measured directly, is the flow pattern inside the volume of heated water. The ideal would be to construct canals to ensure that only a small layer of heated water is in contact with the membrane to ensure optimum vaporization and diffusion through the membrane. Without certain forced-flow patterns, stagnant volumes of water are formed which have a negative influence on the efficiency of the model.

The most important changes to the current model would be the change to the system with more than one stage, utilizing the heat that is generated when vapor is condensed, and a change in materials to enable a more versatile and compact model to be built. With the present testing in the laboratory, electrical pumps are used to circulate the water. The ideal would be to use solar pumps to circulate the water, which would result in a model that could be used in almost any circumstances.

7. CONCLUSIONS

The results of this study show that the solar still can be modelled by using conventional heat transfer theory. The environmental factors that lead to higher production rates are those that result in a higher operating temperature. These are: wind speed, high radiation levels and a high ambient temperature. The most important of these is the solar radiation since it determines the energy input. The other factors simply affect the way the energy is transported from the collecting surface to the environment.

The design aspects of the unit that can be arranged to give high productivity are:

i. a high number of stages;
ii. the use of evaporative cooling to promote heat re-use;
iii. a collector with a low reflectivity; and
iv. a small diffusion gap.

The front gap size was not found to have a significant influence. Again the major influences were those aspects that determine the energy input to the system.

8. RECOMMENDATIONS

The concept of evaporation through a microporous membrane using solar energy has been demonstrated, but several aspects of the project require further development. These include:

i. coupling of the evaporative cooling surface to the unit;
ii. the use of multiple stages;
iii. the testing of different varieties of membranes;
iv. economic optimization; and
v. field testing.

The point regarding membrane development is applicable to the field of membrane distillation in general. Microporous membranes have been shown to wet after a period of time in contact with water containing high levels of saturated salts. It is possible to pretreat water before distillation, but this generally mainly retards rather than prevents the wetting process.

The size of the components used would have an effect on the unsteady-state operation of the unit. In particular the mass of water held in the system would affect the time required for the unit to reach equilibrium conditions. This must be examined in the final optimization of the unit.

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LIST OF SYMBOLS

Temperatures (°K)

T_a	Ambient
T_b	First condensing surface
T_{bag}	Preheater back surface temperature
T_{b1}	Membrane surface of second stage
T_{b2}	Rear surface of membrane bag
T_{b3}	Front membrane surface
T_1	Evaporator canvas surface
T_c	Front cover
T_{cp1}	Clear plastic (preheater)
T_{cp2}	Front cover (preheater)
T_{dist}	Temperature of distillate
T_h	Average water temperature (preheater)
T_{inlet}	Inlet temperature (preheater)
T_{outlet}	Outlet temperature (preheater)
T_s	Effective temperature for radiation
T_{s1}	Second condensing surface
T_w	Water temperature in second membrane
T_{w1}	Water temperature in front membrane

Dimensions (m)

Ac	Area for solar radiation (m^2)
b	Membrane thickness

L	Diffusion path length
l	Characteristic path length
x	Width of water canals (preheater and membrane)
xw	Diffusion path length

Coefficients

Cr	Coefficient for radiation
Dab	Binary diffusion coefficient for water in air
h_e	External convection coefficient (W/m^2.°K)
h_{eb}	External convection coefficient (preheater)
h_i	Internal free convection coefficient
h_{ib}	Internal free convection coefficient (preheater)
h_m	Mass transfer coefficient
h_{wbi}	Free convection coefficient for water
h_{wp}	Forced convection coefficient for bags
k_w	Thermal conductivity of water or air (W/m.°K)

Other

$D_{1,2,4}$	Distilled water (kg/s.m^2)
$J_{1,2}$	Mass flux (kg/s.m^2)
Io	Solar radiation (w/m^2)
v	Kinematic viscosity (m^2/s)
xc	Mole fraction of water at cool surface (sat)
xh	Mole fraction of water at membrane surface temperature (sat)

Greek

ρ	Density (kg/m^3)
α	Thermal diffusity (m^2/s)
β	Volumetric thermal expansion coefficient (K^{-1})
α_{cs}	Absorptivity of clear plastic sheet
α_{cs2}	Absorptivity of front cover
Φ	Membrane porosity
μ	Mass diffusivity
λ	Wavelength (μm)
Σr	Total Reflection

ACKNOWLEDGEMENTS

The research in this project emanated from a project funded by the Water Research Commission and entitled:

"Provision of point-source water by enhanced solar distillation."

The financing of the project by the Water Research Commission is gratefully acknowledged.

The authors wish to thank the following people who assisted with this project:

Dr. H. Saayman for continuing interest.

Prof Tony Fane, Head: UNESCO Membrane Centre, University of New South Wales, for active interest and sharing of his Ph.D.-student.

Mr. Paul Hogan, Ph.D.-student of Prof. Fane, for three months of excellent research on this project.

Prof. Sidney Loeb, University of the Negev, Israel, for a few weeks of very fruitful discussions and a continuing communication on all aspects of the project.

Mr. McCracken, supplier of the internationally known McCracken Solar Stills, for his interest in the South African market and offer of cooperation.

Dr. E.P. Jacobs for his guidance and support throughout this project.

Prof. Harrison, Department Chemical Engineering, University of Stellenbosch, for interest and allowing this as scription work for his Chemical Engineering student, Max Vreugde.

Deon Bezuidenhout and Charl Morkel for their active interest and help.

The staff at the Institute for Polymer Science for their support in this project.

Mrs. Erinda Cooper for compiling and typing of this document.

Mr. F.H. Lancaster for proofreading of the document.

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1. INTRODUCTION

1.1 OBJECTIVES OF STUDY

1. To prove the capability of constructing a foldable, storable, membrane-distillation bag which can be used in emergencies to meet daily requirements of sterile and desalinated water, and a unit to produce 1-10 ℓ of such water per day by the use of solar heat, body heat, heat from hot rocks or cooling by wind.
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3. To develop the appropriate theory behind the system in order to describe the interaction of the various heat- and mass-transfer processes involved.
4. To design and optimize the unit by computer simulation developed from the above-mentioned mathematical model.
5. To produce prototype stills which will be used to evaluate the validity of the computer simulation models.
6. To collaborate in international joint programmes in this development in order to enhance the effectiveness of the final device, and to publish and/or patent it.

1.2 MOTIVATION

In many areas there is a lack of a reliable source of potable water. In most of these areas there is access to large volumes of brackish ground water but these are generally non-potable. This was the main reason for the need to design and create a unit which would use the abundant supply of solar energy to desalinate brackish water, or purify otherwise unfit water, to produce potable water.

Solar distillation is not a new technology. Solar stills have been operating commercially since the late 1800s.[1] The factors that enable solar distillation to compete with other technologies such as reverse osmosis are distance and scale.[2] This includes areas where the alternative is to import water or where the demand for potable water is very small so that the economy of scale is low. If the solar distillation unit is portable, another advantage over conventional desalination methods is achieved..

Conventional solar stills are not considered to be portable devices. The most economical of these, solar ponds, involve the treatment of large volumes of water and generally requires a concrete base and a glass cover. Portability is what makes the proposed unit unique. The majority of the components are proposed to be manufactured of inexpensive plastics. The unit will have a small hold-up volume of water and will be able to be rolled up and transported in a pack. This, in combination with conventional solar distillation, makes such a system possible. Apart from being portable and inexpensive, the system should:

i. be simple to operate;
ii. require low maintenance costs.

All of the above mentioned characteristics give rise to a system that will appeal to a very wide market, for example, for use on life rafts and on hiking trips.

The concept itself is very simple: sunlight enters through a clear film, is absorbed on a black bag that contains water but which will allow the water to evaporate freely. (A similar concept is the use of the canvas water-cooling bags.)

1.3 BASIC PRINCIPLES

1.3.1 MEMBRANE DISTILLATION

Membrane distillation is a process in which water in a heated solution evaporates through a porous membrane. The vapor condenses on a cooling surface on the other side of the membrane. The heated solution and the condensate are separated by a thin, highly porous hydrophobic membrane. The hydrophobic nature of the membrane prevents the passage of liquid through the pores of the membrane, but allows the passage of water vapor through them. The temperature difference produces a vapor-pressure gradient, which causes water vapor to pass through the membrane. The vapor produced is of very high purity, and contains no non-volatile solutes. The basis of this design is air-gap membrane distillation in which are used a membrane surface and a cooling surface separated by an air-gap.

Membrane distillation has many advantages over other membrane processes. It can be operated at low temperatures, (below 100°C) and at atmospheric pressures, and is comparatively free of fouling problems. The basis of separation is the volatility of the water so that any non-volatile solutes are rejected by the membrane.

1.3.2 SOLAR DISTILLATION

A simple system for solar distillation is shown in Fig. 1.1. The non-potable water is admitted to the tray at the bottom where it is heated by absorption of solar radiation. The base of the tray is blackened to facilitate this, since water is substantially transparent to the short-wavelength radiation from the sun. As the temperature of the water increases, the motion of the molecules becomes more vigorous and they leave the surface in increasing numbers. Convection in the air above the surface carries them away so that water evaporates. The rising air current cools on contact with the transparent cover and the vapor in the air condenses on the cover. The condensed water runs down the plate into collector channels at the edges. The cooled air returns to complete the convection current.

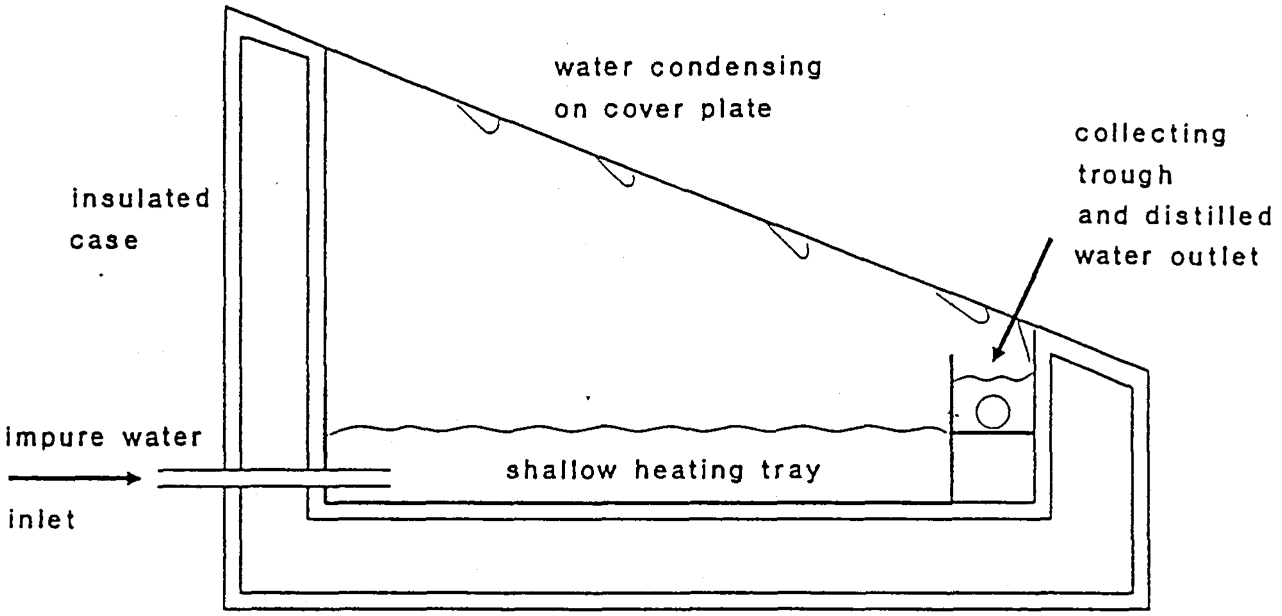

Figure 1.1 : Simple solar still.

For the highest efficiency, it is desirable that the water should condense on the cover plate as a film. Drop-wise condensation causes a large fraction of the incoming sunlight to be reflected away.

1.3.3 EVAPORATIVE COOLING

The concept of evaporative cooling involves the use of the latent heat of vaporization of a liquid to remove heat from a system. Evaporative cooling is far more effective than normal convective cooling. During convective cooling the driving force is the difference between the temperature of the liquid and that of the environment, so that the process is thermodynamically limited to the atmospheric temperature. During evaporative cooling heat transfer occurs as a result of mass transfer from the liquid as a vapor. The driving force for the process is thus a humidity difference, and subatmospheric temperatures can be achieved. This is the principle of operation of canvas cooling-bags.

1.4 PROPOSED DISTILLATION UNIT

The basis of the design is shown in Fig. 1.2. A clear plastic sheet is supported over a black radiation-absorbing membrane bag. This bag rests on a condensing surface, from which it is separated by a thin highly porous spacing material. Sunlight enters through the front sheet and is absorbed on the membrane bag which in turn heats the water. Water evaporates from the front and the rear of the bag and runs down the plastic surfaces to a collection point.

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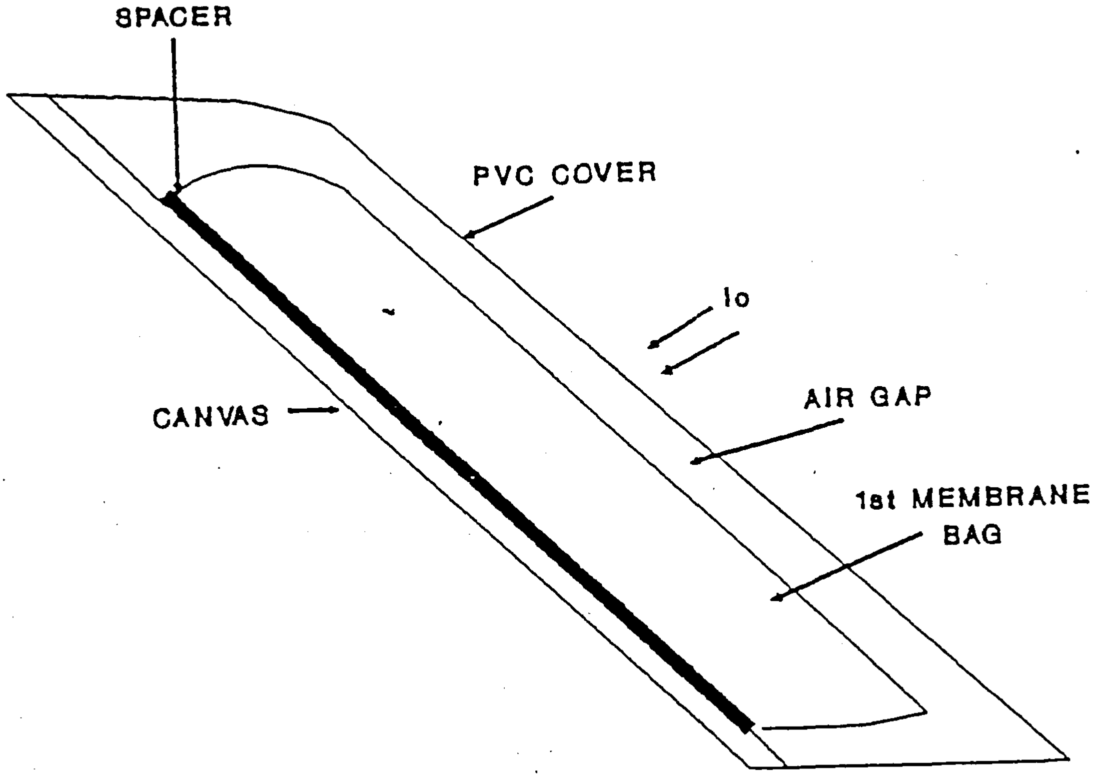

Figure 1.2 : Single-effect unit.

A preheater (Fig. 1.3) is used to preheat the entering water to around 50°C. Again the design of the preheater follows the basic concept of solar collection by the use of black absorbing PVC as the base. A clear PVC sheet is welded above the black PVC to form channels for the water. A clear plastic sheet is supported over the bag itself to reduce heat losses to the environment. Solar radiation passes through the front and second covers and is absorbed by the black PVC. This input of energy causes the water in the channels to be heated.

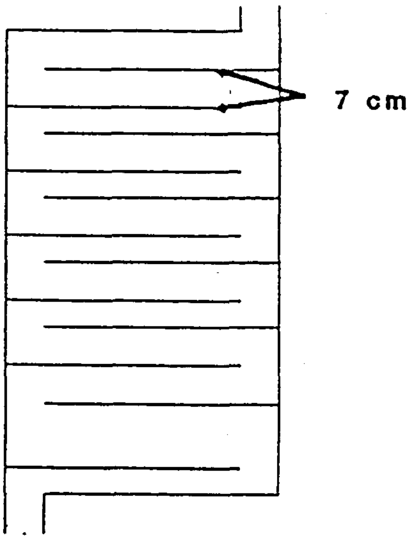

Figure 1.3 : Preheater.

All of the above-mentioned units will be placed at an optimum solar-incidence angle and will face north.

1.5 ALTERNATIVE UNIT

The economics of many distillation processes can be improved by re-using energy. In multiple-effect evaporation systems, for example, this is achieved by using the vapor produced in one stage to supply energy to the next stage. This is the main idea behind the alternative unit in which a double-effect system is used (Fig. 1.4).

It is easy to see that the inclusion of another membrane bag between the first one and the evaporative cooler makes the re-use of energy possible from the front to the rear of the unit. The heat from the first bag will pass through the plastic and heat the water in the second bag. This water will then evaporate to produce more pure distillate.

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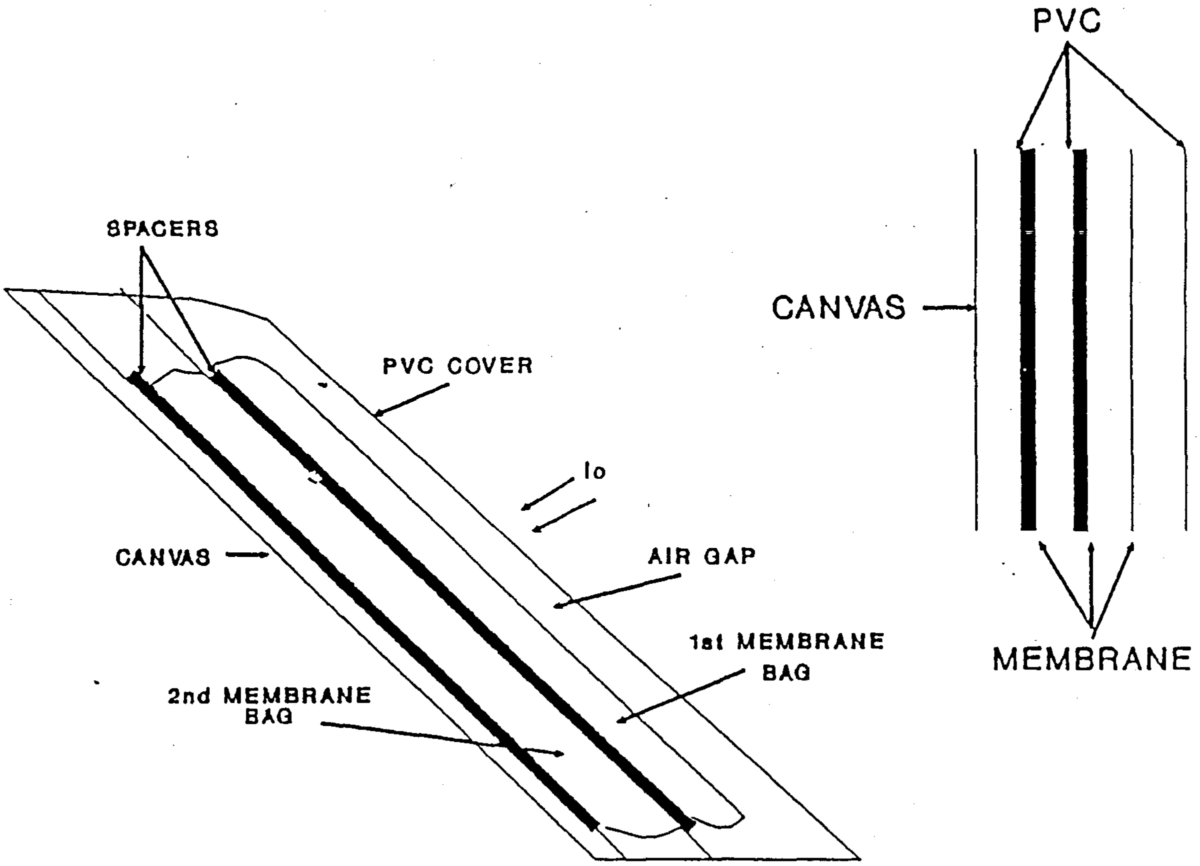

Figure 1.4 : Double-effect unit.

2. LITERATURE SURVEY

2.1 HISTORICAL BACKGROUND

Previous work relevant to the current project relates to membrane distillation, the performance of membrane distillation pilot plants, solar desalination, solar-collecting and evaporative cooling.

The most closely related project to this one is one recently completed in Australia entitled "Solar-Driven Membrane Distillation".[3] That project also aimed to desalinate borehole water, but focused on larger-scale water production (50 kg/day) for domestic use. In this project a hollow-fibre membrane module system was coupled to flat-plate solar collectors, with heat exchangers being used to aid energy recovery. The project showed that the membrane-distillation process could be coupled to a transient solar energy source, and that it produced a high-quality distillate from highly contaminated bore water. The economics of the unit were found to be unfavorable because of the high cost of the heat-exchange equipment and the pumping requirements.

The present project seeks to avoid these difficulties by recovering heat internally through inexpensive plastic surfaces, and requires only a low-capacity recirculating pump. The use of plastic instead of stainless steel also makes the device cheaper and more easily portable.

The use of plastics in solar-driven evaporator systems is also mentioned in a paper entitled "Plastic Solar Collectors for Low Energy Applications".[4] This research focused on the use of plastic collectors in application where the fluid temperatures would be in the region of 60°C. It was found that the low density of polymers permitted construction of solar collectors of low mass (portable). It was also found that the maximum working temperatures of these collectors were not to exceed 80°C. "Plastics in Solar Energy Collectors"[5] also mentions a few useful facts concerning this project. It emphasizes that plastics offer design flexibility, parts consolidation, mass reduction, corrosion resistance and overall savings. Emphasis is placed on the way in which plastics can be used to reduce heat losses from a system and this in combination with the following was useful in the design of both the preheater and the distillation units and on the choice of materials to be used in their construction:[6]

2.1.1 TRANSPARENT-COVER PROPERTIES

1. Must have a high transmittance (Tr) over the solar spectrum ($0{,}3\ \mu m < \lambda < 2\ \mu m$).
2. Must have a low emittance (ϵ) to reduce radiation losses.
3. Should be stable at high temperatures.
4. Must be resistant to atmospheric conditions (e.g. hail).
5. It should reflect thermal radiation from the heated absorber over the spectrum ($2{,}5\ \mu m < \lambda < 100\ \mu m$).
6. It should have a low absorbance (α) over the solar spectrum.

2.1.2 ABSORBER PROPERTIES

1. Must have a low emittance (ϵ) to reduce radiation losses.
2. It should have a high absorbance (α) over the solar spectrum.
3. Should be stable at high temperatures (60°C).
4. Must be resistant to atmospheric conditions.

Membrane distillation has received considerable attention over the past twenty years, although it has had little commercial success. Research relevant to this project can be found in a paper entitled "Membrane Distillation - A Theoretical Study of Evaporation Through Microporous Membranes".[7] The project described there aimed to investigate the dependance of mass transport and heat transport upon different process and membrane parameters involved in air-gap membrane distillation. A membrane similar to the one used in that project was used here and an evaporation flux equation was derived from the different mass and energy balances which could be used to predict the evaporation rate in the present model. It can be seen from this research that the rate of evaporation is strongly influenced by the following:

1. An increase in the temperature of the heated solution increases the vapor pressure, and hence the driving force for evaporation. This means that the rate of evaporation increases if the temperature of the heated solution is increased even though the temperature difference between the heated solution and the condensing surface is still constant.
2. The rate of evaporation decreases as the distance of diffusion from the heated solution to the cooling surface increases.

Many investigations have been conducted on the use of heat recovery as a means to improve the efficiency of these solar devices.[1] Plants have been demonstrated to achieve up to four effects.[2] The two important factors affecting the viability of a solar energy source are the cost of transporting water and the capacity of the plant. A previous study demonstrated that solar distillation was a feasible option on a large scale (>100 m^3/day) at distances greater than 160 km from a town water source.[8] Alternatively, the system was suitable if the capacity was small. The economics of a low capacity unit operating in a remote region would thus appear to be encouraging. The analysis was based on solar water being produced at between 2,4 and 3,0 c/ℓ.

One of the main advantages of the proposed unit is that it can be tilted at an optimum angle towards the sun. At the equator a fixed horizontal surface represents the optimum surface for solar-still installations. At different latitudes tilting of the surface increases the amount of solar energy reception. This consideration also resulted in a new and simplified design of solar-still.[1] A roof-type solar still could be tilted by using a porous pad, fed continuously with sea water at one end and equipped with a brine-collecting channel at the other end. A plastic sheet is supported over the structure to form a condensing surface from where the water could trickle down to a collection point. This study also shows that a newly designed solar still should be able to produce at least 4,8 kg/(m^2.day) of distilled water.

Micorporous hydrophobic membranes were examined for possible use in evaporative cooling of water in "Membrane Evaporating Cooling".[9] It was found that the use of membranes for evaporative cooling would be more effective than canvas cooling bags, and this should be considered when optimizing this unit, although it should be kept in mind that this would increase the cost of the distillation unit.

3. EXPERIMENTAL

3.1 THEORETICAL BACKGROUND

3.1.1 HEAT- AND MASS-TRANSFER IN MEMBRANE DISTILLATION

Heat transfer in membrane distillation occurs by three mechanisms: 1) latent heat, 2) conduction/convection, and 3) radiation. Since conduction, convection and radiation do not result in vapor transport they are treated as heat losses. The latent heat is associated with the passage of vapor across the membrane, and is generally quantified by means of some form of flux equation. The conduction/convection occurs because of a temperature difference between two surfaces separated by a polymer/air layer. Conduction and convection do not occur simultaneously. At small temperature differences and gap sizes conduction will occur. Above certain critical values of these parameters the conduction mechanism will be replaced by forces of natural convection. The radiation also occurs because of a temperature difference between the two relevant surfaces.

Since heat transfer by conduction/convection and radiation does not contribute to the vapor transport it is treated as heat loss. It is thus desirable to minimize these forms of heat transfer. The operating conditions that increase the proportion of heat transfer by vapor are high operating temperatures and low pressures.

Conduction and convection vary in proportion with the temperature difference between the heated solution and the cooling surface. The driving force for vapor transport is not the above temperature difference, however, but rather the vapor pressure difference which varies exponentially with temperature. The result is that convection/conduction are not influenced by the absolute temperatures if the actual temperature difference remains constant. Since absolute temperature has a positive effect on the vapour-transport driving force, the proportion of heat loss decreases as the temperature is increased.

A lower operating pressure reduces the amount of air separating the hot and cold surfaces which in turn reduces the thermal conductivity of the path, and increases the resistance to conduction and convection heat transfer. If the pressure is reduced the resistance to vapor transport is also reduced. In the practical case it is difficult to reduce this pressure without the addition of complex vacuum equipment.

3.1.2 ENERGY USAGE IN A SOLAR DISTILLATION UNIT WITH PREHEATER

3.1.2.1 Heat- and mass-transfer processes

In the steady state the amount of energy absorbed by the system is equal to that released to the environment. This energy release follows a complex path from the collecting surface, through the fluids and surfaces to the external surroundings.

Energy in the form of solar radiation is initially incident on the membrane or collecting surface. Some energy is also absorbed by the clear cover above the membrane, but this would typically be less than 10% of the total solar radiation input, depending on the material being used. In the front section heat is transferred to the cover by vapor transport, convection and radiation to the cover. This energy is then dissipated to the environment by radiation and convection.

Energy is also liberated from the rear membrane surface as radiation, conduction and as a vapor. This energy is transferred to the rear condensing surface.

3.1.2.2 Energy re-use

The economics of many evaporative processes can be improved by the re-use of energy.

The most important aspect here is that the heat travels in two directions from the collection surface. The distinction between heat transport from the front and rear of the collecting surface is an important one. Heat transfer from the front occurs between the membrane surface and the clear cover, and from there to the environment. This energy cannot be re-used, because any subsequent stages would lower the energy collection.

The surfaces involved in the rear heat transfer are behind the energy-collecting surface, so that although they also add resistance to the heat transfer step they do not reduce the energy input to the unit. This energy may be re-used.

The energy liberated at the rear surface passes through to the water on the outer side. From here it passes through a water layer to the rear of the cavity. This surface is an additional membrane in contact with a spacer and a condensing surface so that as the energy passes through the secondary bag it is also partially liberated as a vapor, and further distillation occurs.

At any energy input level the steady-state heat loss to the environment is fixed. While the amount of energy removed may not be altered it is possible, however, to arrange the manner in which it is removed. A device that promotes the rear heat transfer, and thus energy re-use, can greatly improve the efficiency of the unit. An evaporative cooler is used to direct the heat to the rear of the unit.

3.1.2.3 Preheater

The following are the energy balances for the proposed preheater design, based on the relevant equations [10].

A. Assumptions

1. The balances are for steady-state so that no heat-accumulation terms are included.
2. Conduction losses to the rear of the unit are negligible. This assumption can be made since an insulating material will be present at the back of the unit.
3. The surfaces are thin, and their temperatures can be considered to be uniform.
4. All calculations are based on a 1 m^2 surface.

B. Equations

Overall

Radiation collected + Enthalpy of inlet stream = Losses from front cover + Enthalpy of outlet stream.

IN: Insulation – reflection losses + inlet enthalpy

$$Io(1 - \Sigma r) + (Bi)(Cp)(T_{inlet})/Ac$$

OUT: Front cover: convection, radiation from surfaces to atmosphere

Water: enthalpy of outlet stream

$$Bi(Cp)(T_{outlet})/Ac$$

Rear bag surface

Radiation collected = Energy passing from rear to front.

IN: Insulation – absorption losses by plastic covers

$$Io(1 - (\alpha_{cs} + \alpha_{cs2})$$

OUT: Forced convection from rear to front

$$(h_{wp})(T_{bag} - T_h)$$

Front bag surface (clear plastic)

Radiation collected = Energy passing from rear to front of bag + Losses between the front of the bag and the front cover and environment.

IN: Forced convection from rear to front, absorption of insulation

$$(h_{wp})(T_h - T_{cp1}) + Io(1 - \alpha_{cs})\alpha_{cs2}$$

OUT: Convection and radiation losses to the front cover

$$(h_{ib})(T_{cp1} - T_{cp2}) + Cr(T_{cp1}{}^4 - T_{cp2}{}^4)$$

Front cover

Energy from front bag surface + Some radiation absorbed = Energy lost to environment.

IN: Energy from front bag surface to cover, convection and radiation, + absorbed component of insulation

$$Io(\alpha_{cs2}) + (h_{ib})(T_{cp1} - T_{cp2}) + Cr(T_{cp1}{}^4 - T_{cp2}{}^4)$$

OUT: Energy lost by convection and radiation to the environment

$$(h_{eb})(T_{cp2} - T_a) + Cr(T_{cp2}^4 - T_s^4)$$

3.1.2.4 Distillation unit

The following are the energy balances for an evaporatively cooled solar still with two stages, based on the relevant equations [10]. These equations are similar to that for the single-stage unit with evaporative cooling, the only difference being that it has two energy balances.

A. Assumptions

1. The balances are for steady-state, so that no heat-accumulation terms are included.
2. The thin film of condensate on the plastic surface is sufficient to prevent radiation from the first membrane surface to the environment.
3. The flux between the rear membrane surfaces and the condensing surfaces is mainly by diffusion, and the resistance through the membrane is considered.
4. The flux in the front cavity is by free convection, with the resistance of the membrane negligible.
5. The surfaces are thin, and their temperatures can be considered to be uniform.
6. All calculations are based on a 1 m^2 surface.

B. Equations

Overall

Radiation collected = Losses from front cover + Losses from evaporative cooler.

IN: Insulation – reflection losses + inlet enthalpy from preheater water

$$Io(1 - \Sigma r) + Bi(Cp)(Th)/Ac$$

OUT: Front cover: convection, radiation from surface to atmosphere

$$(h_e)(T_c - T_a) + Cr(T_c^4 - T_s^4)$$

Evaporative cooler: convection, radiation and evaporation from surface to atmosphere

$$(h_e)(T_a - T_1) + Cr(T_1^4 - T_s^4) + h_m(h_e)(p_{sat,t1}/T_1 - p_{atm}/T_a)$$

Water: Enthalpy of brine and distillate

$$(D1 + D2 + D4)(Cp)(T_{dist}) + (Bi/Ac - D1 - D2 - D4)(Cp)(T_h)$$

Evaporative cooling surface

Losses from canvas surface to environment = Energy passing from second condensing surface to canvas.

IN: Free convection between condensing surface and canvas

$$h_{wbi}(T_{s1} - T_1)$$

OUT: Convection, evaporation and radiation to environment

$$(h_e)(T_a - T1) + Cr(T_1{}^4 - t_s{}^4) + h_m(h_e)(p_{sat,t1}/T_1 - p_{atm}/T_a)$$

Second condensing plate

Energy from condensing plate to canvas = Heat passing from third membrane surface.

IN: Latent heat associated with flux, conduction and radiation between third and second condensing surface.

$$kw/xw(T_{b1} - T_{s1}) + J_3(h_{fg2}) + Cr(T_{b1}{}^4 - T_{s1}{}^4)$$

OUT: Free convection between condensing plate and canvas

$$h_{wbi}(T_{s1} - T_1)$$

Third membrane surface

Energy lost between third membrane surface and second condensing surface = Energy passing between first condensing surface and membrane.

IN: Forced convection between first condensing plate and third membrane surface

$$h_{wp}(T_w - T_{b1})$$

OUT: Latent heat associated with flux, conduction and radiation between third membrane and second condensing surface

$$kw/xw(T_{b1} - T_{s1}) + J_3(h_{fg2}) + Cr(T_{b1}{}^4 - T_{s1}{}^4)$$

First condensing surface

Energy passing between first condensing surface and third membrane = Energy transferred from second membrane surface to first condensing surface

IN: Latent heat associated with flux, conduction and radiation between second membrane and first condensing surface

$$J_2(h_{fg2}) + kw/xw(T_{b2} - T_b) + Cr(T_{b2}{}^4 - T_b{}^4)$$

OUT: Forced convection between first condensing surface and third membrane

$$h_{wp}(T_{b2} - T_b)$$

Second membrane surface

Energy transferred to first condensing surface = Energy passing from front to rear of the membrane bag.

IN: Forced convection from front to rear of membrane bag

$$h_{wp}(T_{w1} - T_{b2})$$

OUT: Latent heat associated with flux, conduction and radiation between second membrane and first condensing surface

$$J_2(h_{fg2}) + kw/xw(T_{b2} - T_b) + Cr(T_{b2}^4 - T_b^4)$$

First membrane surface

Radiation collected = Energy passing from front to rear of bag + Losses between the front of the bag and the front cover and environment

IN: Insulation – absorption losses

$$Io(1 - \alpha_{cs2})$$

OUT: Forced convection from front to rear of bag, convection, radiation and latent heat with flux to front cover

$$h_{wp}(T_{b3} - T_{w1}) + h_i(T_{b3} - T_c) + J_1(h_{fg1}) + Cr(T_{b3}^4 - T_c^4)$$

Front cover

Energy from membrane surface + Some radiation absorbed = Energy lost to environment.

IN: Energy from front membrane surface to cover by flux, convection and radiation, + absorbed component of insulation + heat form condensation

$$D1(h_{fg4}) + h_i(T_{b3} - T_{w1}) + J_1(h_{fg1}) + Cr(T_{b3}^4 - T_c^4) + Io(\alpha_{cs2})$$

OUT: Energy lost by convection and radiation to the environment

$$h_e(T_c - T_a) + Cr(T_c^4 - T_s^4)$$

– minus
+ plus
= equal to

3.2 CORRELATIONS

3.2.1 HEAT TRANSFER

For convection to the environment the heat transfer coefficient for laminar flow can be calculated from the following correlation:[11]

$$Nu = (h_{e/eb})(1)/k = 0{,}664(Re^{0{,}5}(Pr^{0{,}33})$$

Free convection occurs when buoyancy forces are sufficient to overcome viscous forces. The test for this is that free convection will occur when the Raleigh number exceeds 1708:

$$Ra = Gr.Pr = (g)(\beta)(1^{3})(\Delta t)/v.\alpha) > 1708$$

The internal free-convection coefficients are calculated from correlations relating the Grashof number to the Nusselt number. The cavity between the membrane bag and the front cover is equivalent to a flat plate heated from below at 45°. For this situation the correlation by Tabor is used; where the Grashof number is defined as follows:

$$Nu = 0{,}093(Gr^{0{,}310}) = h_{i/wb1/ib}(1)/k$$

$$Gr = (g)(\beta)(1^{3})(\Delta t)/v^{2})$$

The canvas cooler is equivalent to a rectangular cavity heated from above at 135°. Correlations for this situation relate the heat-transfer coefficient to the Nusselt number that occurs at an angle of 90°.

$$Nu(\sphericalangle\ ) = 1 + [Nu(90\tfrac{1}{2}) - 1]\sin(\sphericalangle\ )$$

The internal forced convection in the canals is calculated from the following correlations for fully developed laminar flow:[11]

$$Nu = 4{,}558 = h_{wp/wb1} \cdot d_{h}/k$$

$$d_{h} = 4(0{,}1156\ (\pi)(x^{2})/(2{,}375.x)$$

The equation for the equivalent diameter was calculated by means of a cross-section graph drawing of a water canal, and calculating the area and perimeter.

The factor Cr is not the same for each equation, and simply serves to collect the Stefan-Boltzman constant, emissivity, or transfer factor.

3.2.2 MASS TRANSFER

Two kinds of mass transfer occur in this system. In the front cavity the mass transfer occurs by convective transport. The mass transfer is found by use of the appropriate heat-transfer coefficient and the mass/heat transfer analogy:

$$h_{m} = Ma(h)/[(\rho)(R)(Cpa)(\alpha/D_{ab})^{2/3}]$$

In the subsequent mass transfer regions vapor diffuses through an air gap separated by a thin spacer. An equation proposed by Jonnson[8] for mass transfer between a "Goretex" membrane and a condensing surface is as follows:

$$J = 1{,}138 \times 10^{-6}[b/\Phi\ .T_h^{0{,}5}) + L/(T_c^{0{,}5})]^{-1}.\ln[(1 - xc)/(1 - xh)]$$

3.3 COMPUTER SIMULATION

Two simulations were done using the equations mentioned in the section above:

1. a single-effect unit with cooling and a preheater (MAXSIN.PAS); and
2. a double-effect unit with cooling and a preheater (MAXDUBB.PAS).

A representative or normal value was chosen from the literature for each variable used in the simulation. These values and references are shown in the "CONST" section of the single-effect distillation unit. The sensitivity study was done by keeping all but one of the variables at their normal values while changing the value of the variable investigated.

The simulations were done of the preheater section and the distillations unit section. The unknown values from the equations, mentioned above, were solved using the "Halving of the Interval" method, and each energy balance was done separately. This method requires that starting values be obtained before the method can begin. This is done by choosing an upper and a lower limit for the unknown value and completing the iteration between these two values.

The programs are on the floppy disc presented with the report. Printouts are included in Appendix 1.

3.4 EXPERIMENTAL

The primary aim of the prototype was to construct a very basic and inexpensive unit for the purpose of checking some of the results obtained in the simulation model, and to show the basic concept of the idea. This is a single-effect unit without evaporative cooling which differs from the simulation model. Another difference is that the wood used as the base of the unit acts as a good insulator of heat and evaporation should not occur at the back of the unit. As a result of this the only production comparable to that of the simulation model, will be the production in the front of the unit.

Fig. 3.1 shows a schematic diagram for the experimental prototype unit. The main structure of the unit is a wood base, covered with thin plastic (PVC), to support the membrane bag at an angle of 45°. Thin horizontal steel rods are placed 2,5 cm from the base to keep the bag from bulging between the wood base and the steel rods and remain coupled to the in- and outlet lines. A clear plastic sheet is supported over the structure, 3,5 cm from the bag, to act as a condensing surface. The dimensions of the bag are 0,5 m × 0,5 m.

The warm-water bath is kept at a constant temperature by means of a thermocouple and a heating element. Water is then circulated through the bag and the flow rate is regulated by the use of valves 1 and 2. A centrifugal pump is used to circulate the water. The temperature difference between the bag and the clear cover causes the water to evaporate through the membrane.

Water vapour condenses on the plastic cover after which water runs down the cover to a collection point. The hourly rate of distillation can be measured and compared with the results obtained with the computer simulation (front production). The results are compared by using runs with water at the same temperature in both the simulation and the experimental unit.

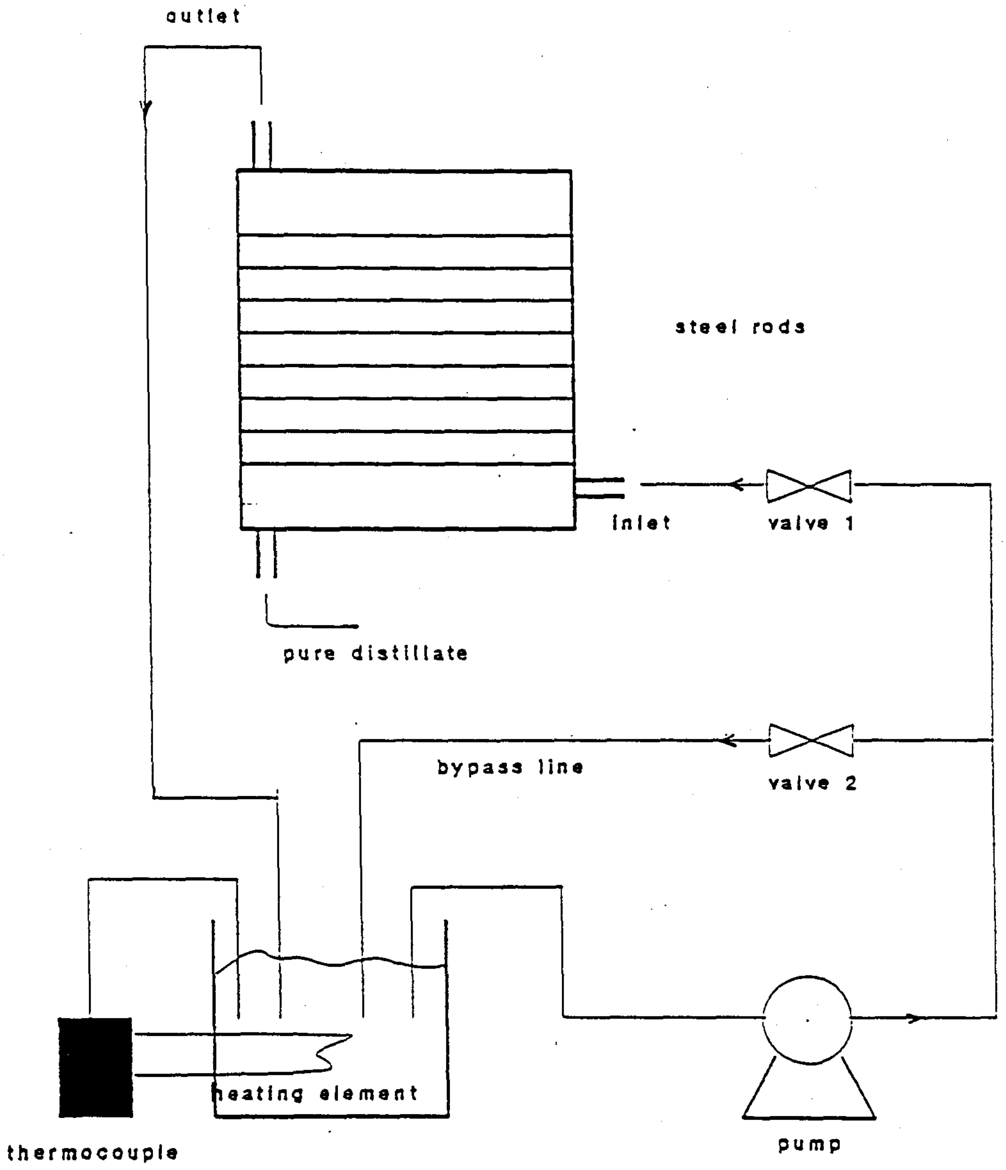

Figure 3.1 : Experimental unit.

4. RESULTS AND DISCUSSION

The results presented in this section are those obtained from the computer simulation sensitivity study. The systems investigated were:

i. single-stage with evaporative cooling and preheating;
ii. double-stage with evaporative cooling and preheater.

4.1 PREHEATER

Results are shown in Tables 1 to 4 in Appendix 2.

Figs. 4.1 to 4.3 show the sensitivity of the preheater to environmental conditions. Fig. 4.1 shows the temperature profiles of the various surfaces at a range of energy inputs. Higher temperatures result at high solar radiation levels. The same rise in temperature can be seen in Fig. 4.2 where the variable input is ambient temperature. It is important to note that this rise is intensified on the profile of the cover temperature since this surface is in direct contact with the environment.

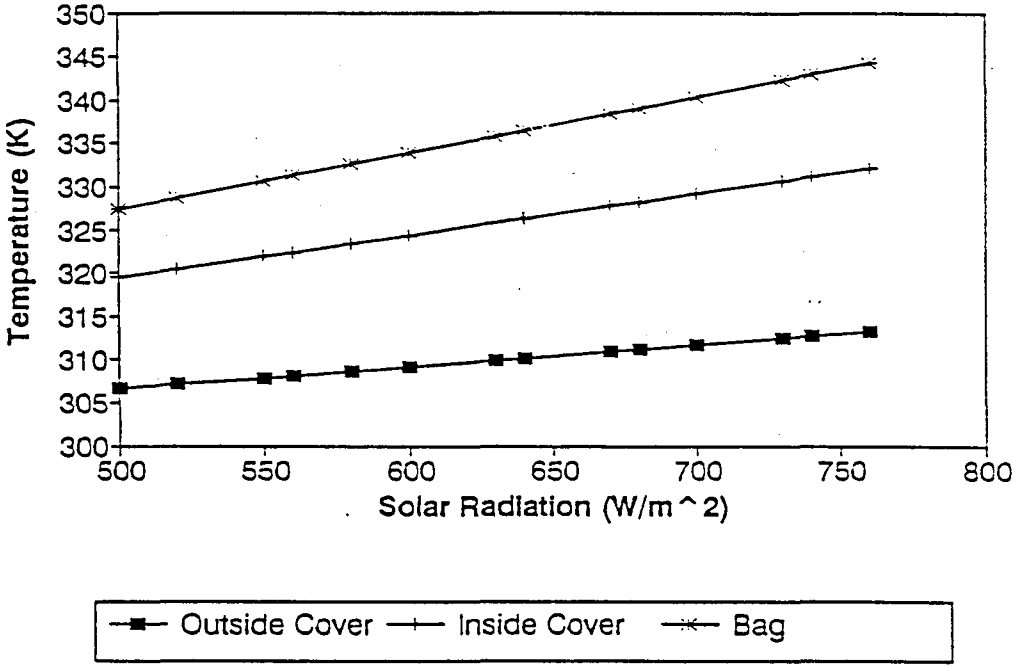

Figure 4.1 : Preheater Results : Io vs. Temperature.

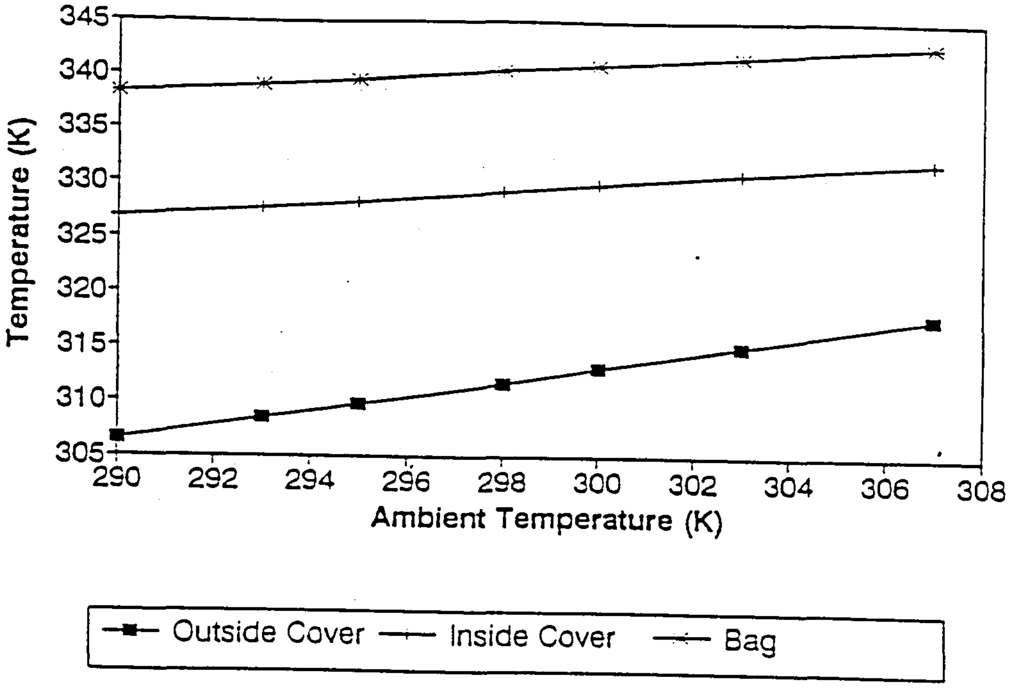

Figure 4.2 : Preheater Results : Ta vs. Temperature.

Fig. 4.3 shows the influence of wind speed on the different surfaces. Low wind velocities, corresponding to a low external convection coefficient, lead to slightly higher surface temperatures which are favourable for the generation of higher preheater outlet temperatures. The change in windspeed has a minor effect on the temperatures since it does not affect the energy input to the system.

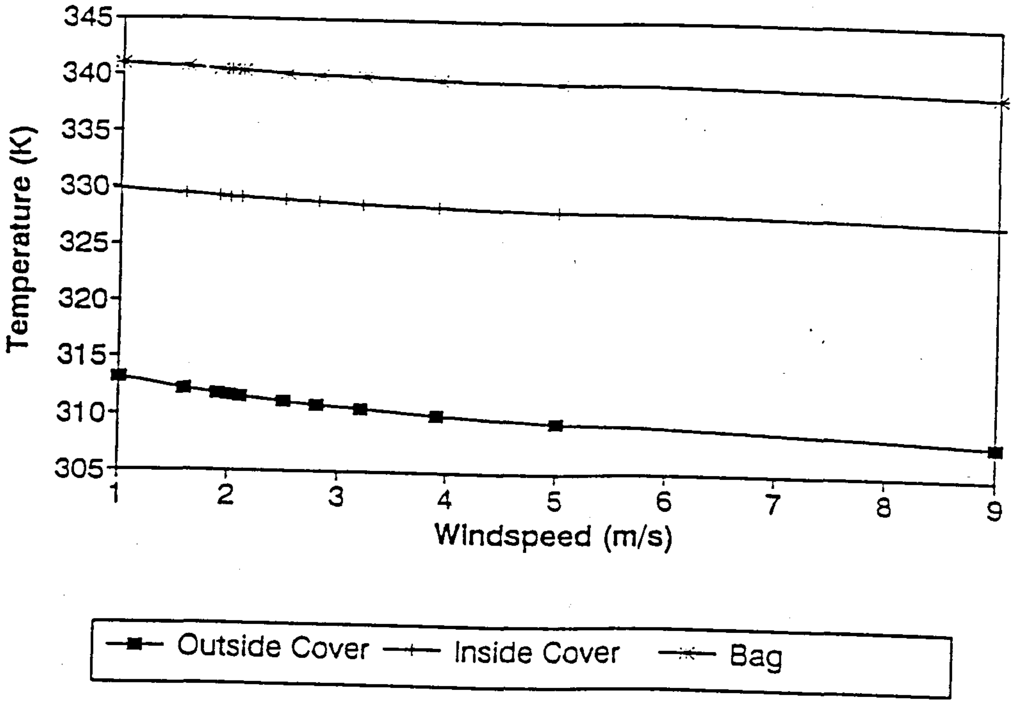

Figure 4.3 : Preheater Results : Windspeed vs. Temperature.

Fig. 4.4 shows the sensitivity of the preheater to design conditions. Higher percentage reflectivity results in lower operating temperatures. Design and materials, as well as varying solar incidence angles, are important in minimizing the total reflectivity of the preheater.

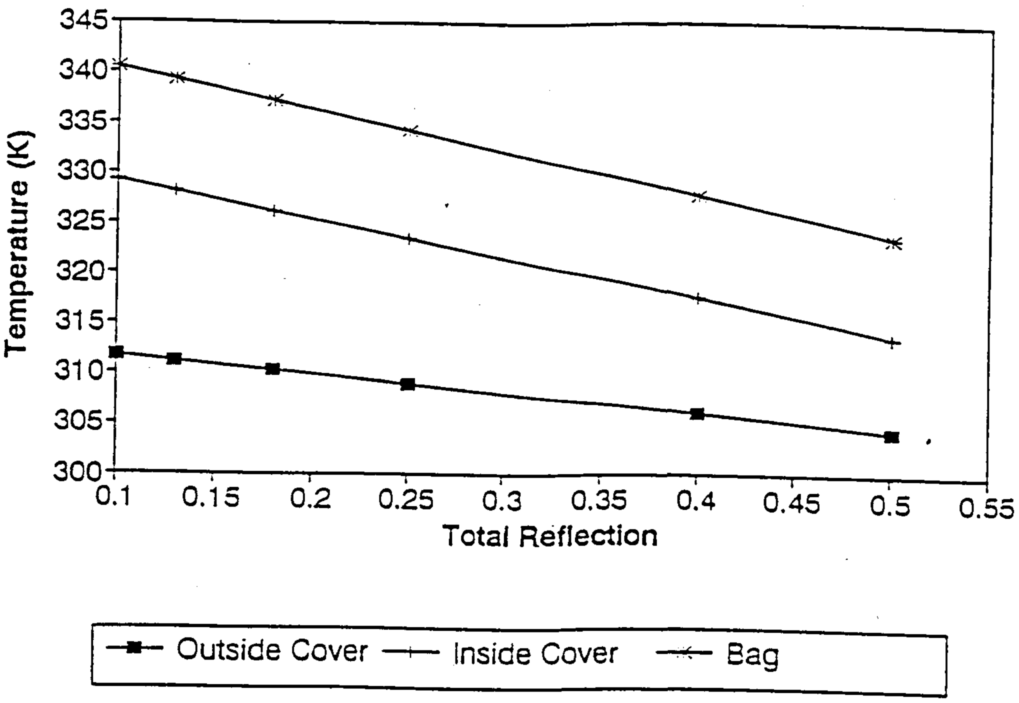

Figure 4.4 : Preheater Results : Total Reflectance vs. Temperature.

The preheater outlet temperature varies from 40 to 60°C depending on the environmental and design conditions, which results in temperature differences of 20 to 40°C/m^2 of preheater surface. When the flow rate through the bag was doubled to 10 ℓ/h the outlet water temperature was 43°C compared with an outlet temperature of 58°C when a flow rate of 5 ℓ/h was used.

4.2 DISTILLATION UNIT

4.2.1 SINGLE-EFFECT UNIT

Results are shown in Tables 5 to 12 in Appendix 2.

4.2.1.1 Sensitivity to environmental conditions

Fig. 4.5 shows the temperature profiles for a single-stage system for three different solar energy inputs. The ambient temperature was 298°K in all cases. There was a sharp rise in temperature between the environment and the front cover, with the peak temperature at the collecting surface (membrane bag outer surface). The temperature gradient from this surface to the rear of the unit is much more gradual.

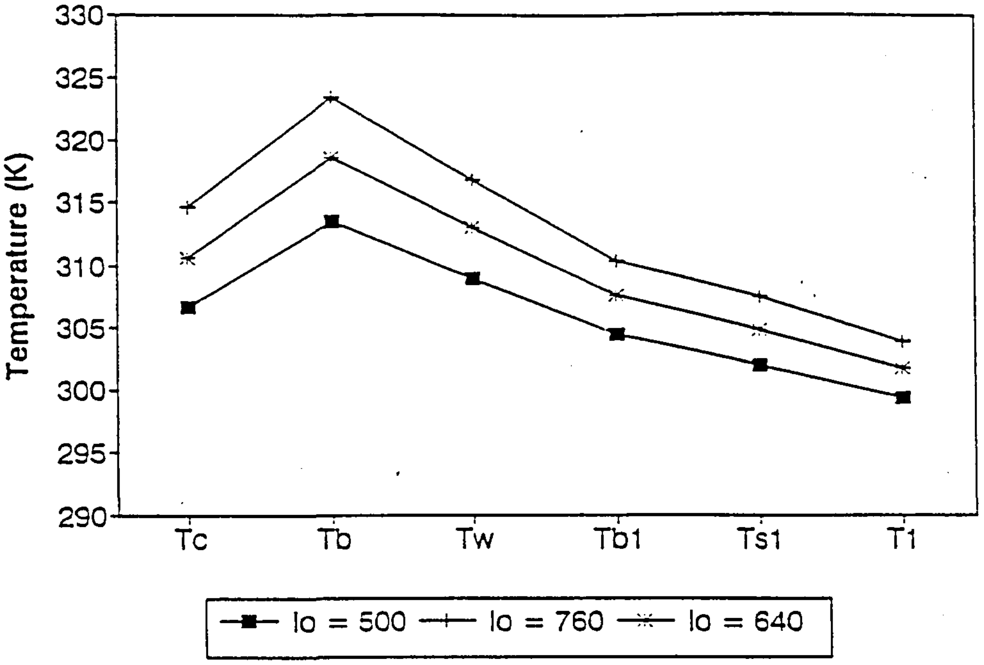

Figure 4.5 : Surface Temperature Profile : Io vs. Temperature.

Fig. 4.6 shows the sensitivity of the single-stage system to the energy input. Higher production was obtained at high solar radiation input levels. The production through the diffusion gap at the back of the membrane bag was also noticeably higher than that through the air gap in the front, and this is also shown in all of the following figures.

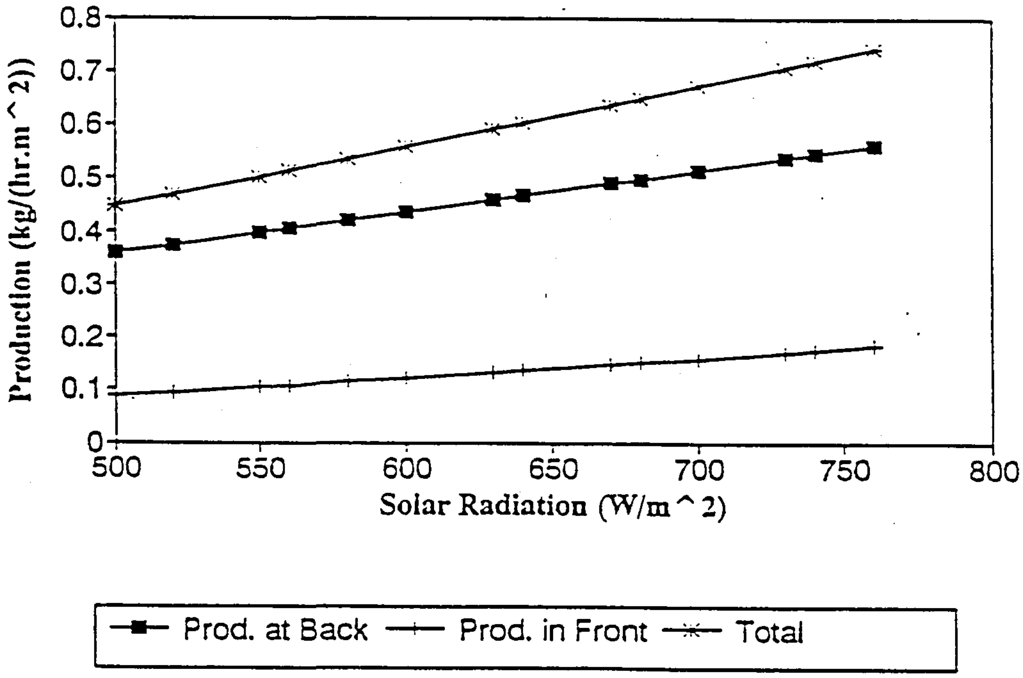

Figure 4.6 : Membrane Bag : Production vs. Radiation.

Fig. 4.7 shows the influence of the ambient temperature on the performance of the single-stage system at a constant solar radiation input. There is a slight rise in the production unit with an increase in the ambient temperature. This is a result of the increased proportion of heat transfer by vapour transport at higher temperatures.

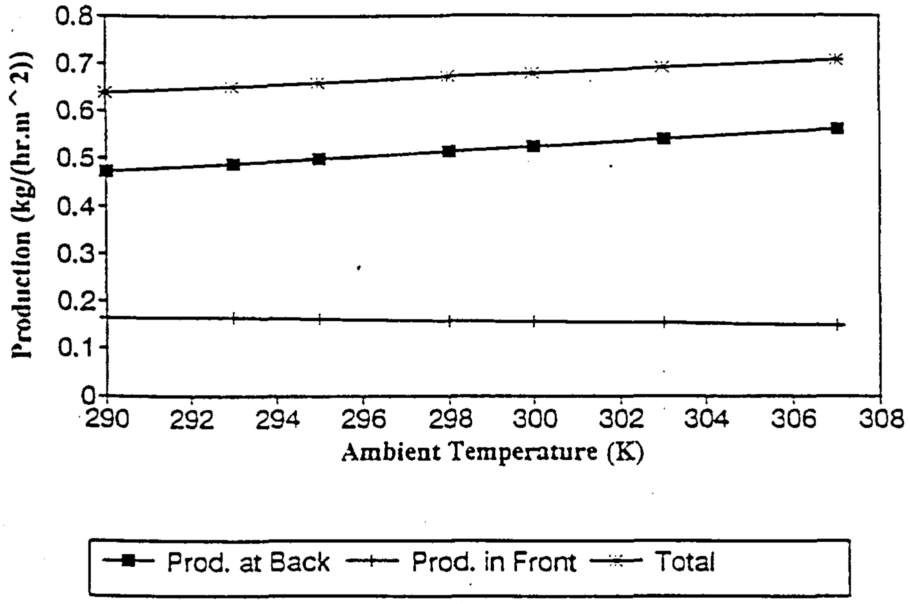

Figure 4.7 : Membrane Bag : Production vs. Ambient Temperature.

Fig. 4.8 shows the effect of windspeed on the productivity. The windspeed has a relatively minor effect on the productivity of the unit. Again, this occurs because the windspeed does not have an effect on the energy input to the system. A low windspeed implies a low external heat transfer coefficient between the unit surface and the environment. To maintain the rate of heat transfer at low windspeeds the temperature of the unit surface must increase. This increases the temperature throughout the unit, which is favourable for distillation.

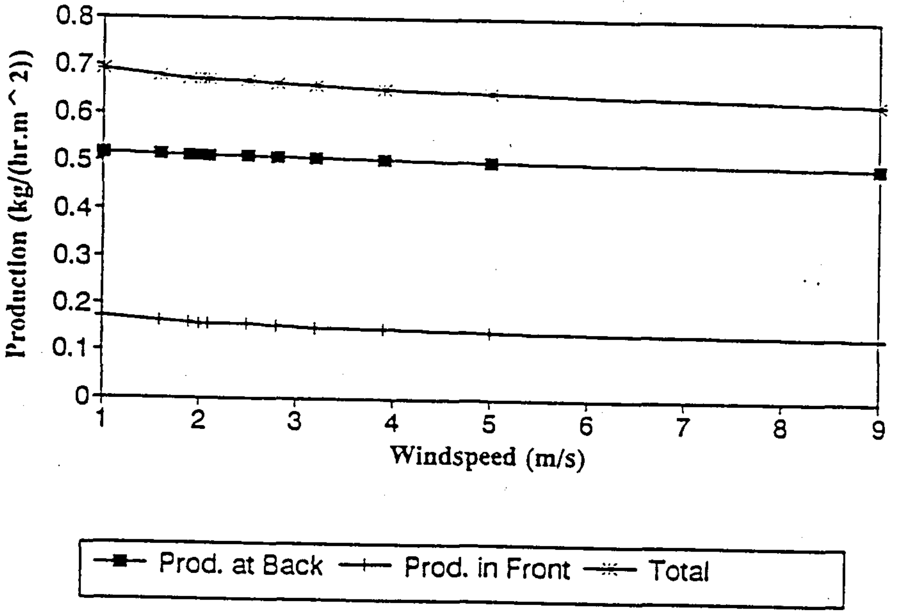

Figure 4.8 : Membrane Bag : Production vs. Windspeed.

Fig. 4.9 shows the influence of humidity on the productivity. It shows virtually no effect on the total production of the system although a slight increase in front production and a decrease in back production is noticeable. This occurs because the evaporative cooling is less effective at higher humidities, which in turn results in more heat being available for evaporation in the front and less at the back.

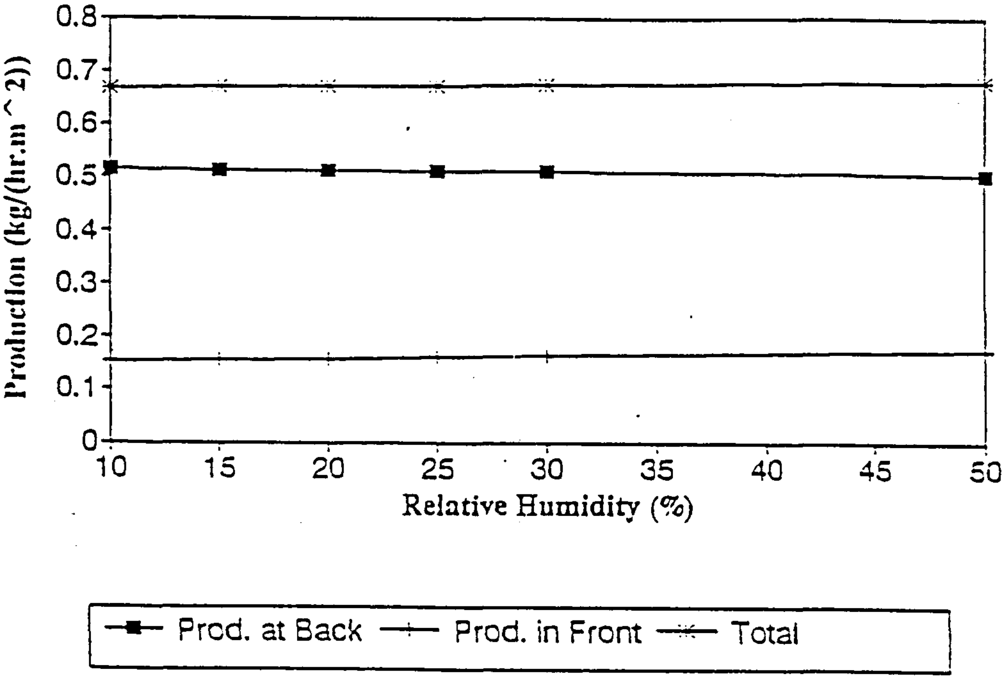

Figure 4.9 : Membrane Bag : Production vs. Relative Humidity.

4.2.1.2 Sensitivity to design variables

One of the most important design variables to consider when designing a solar distillation system is the total reflectance of the system. This can be seen from Fig. 4.10 which shows a steep decrease in production rates as the total reflectance increases. Materials of construction, as well as varying solar incidence angles, are important in minimizing the total reflectance of the unit.

Fig. 4.11 shows the effect of change in the size of the diffusion gap, that is, the gap between the membrane bag and the condensing surface in the rear section at 40 mm. A larger diffusion gap results in a lower total production rate. This is because a larger diffusion gap increases the resistance to heat transfer in the rear of the unit. It is, however, interesting to note that the front production increases, because more heat is available for production in the front.

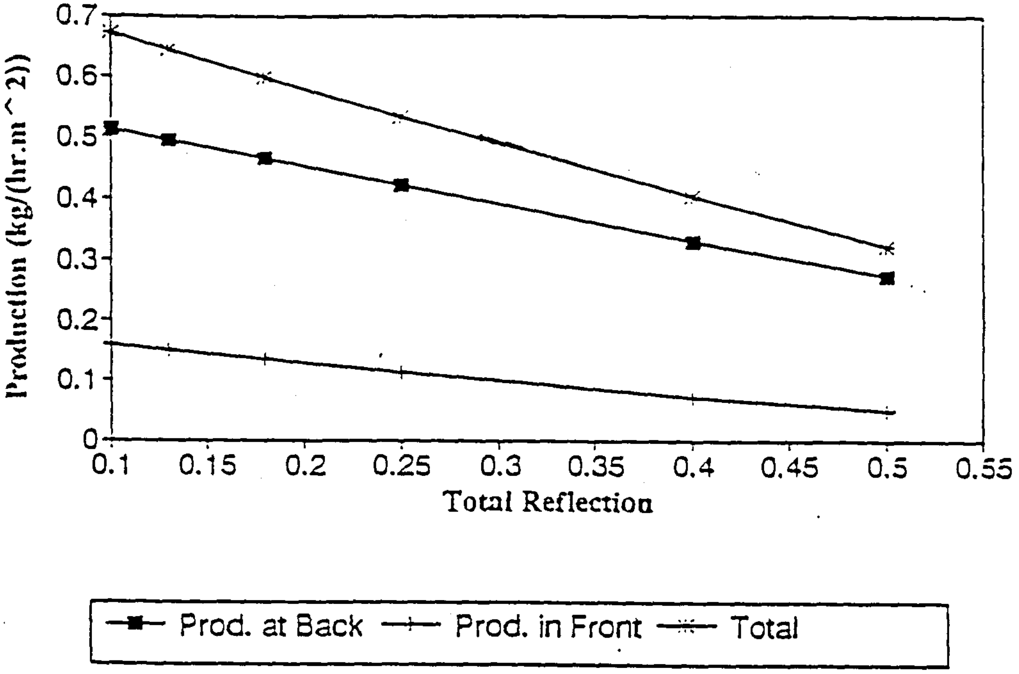

Figure 4.10 : Membrane Bag : Production vs. Reflection.

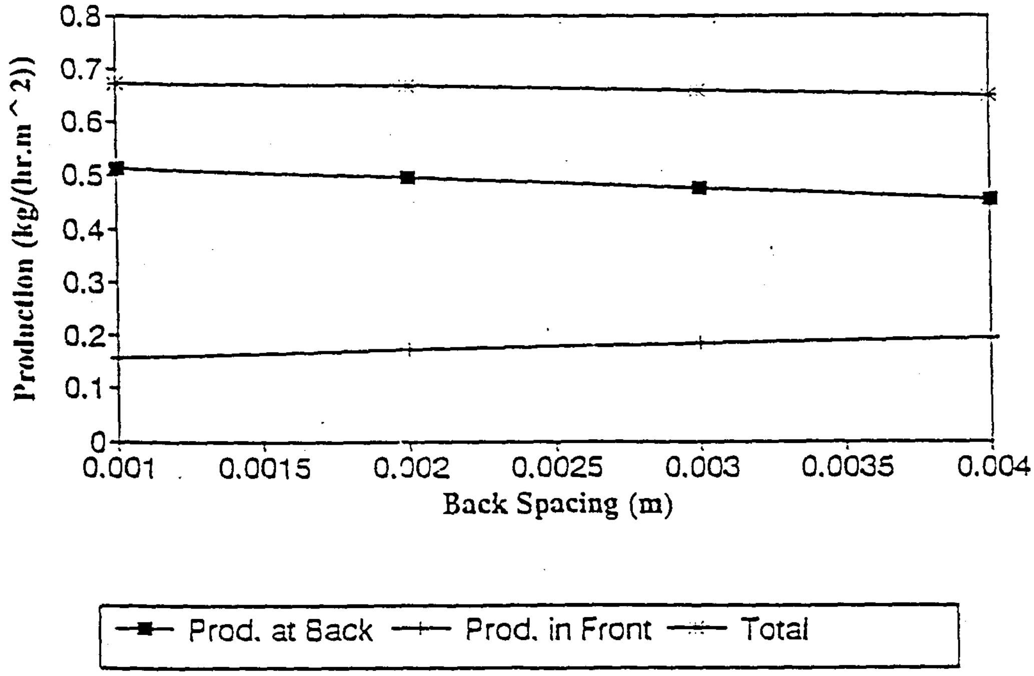

Figure 4.11 : Membrane Bag : Front Spacing = 4 cm.

Fig. 4.12 shows the effect of the front gap dimensions on the productivity of the unit. There was little or no effect on the productivity. This illustrates one of the most important differences between the heat transfer at the front and at the rear of the unit. Whereas in the rear section vapor and conducted heat diffuse across an air gap, in the front the process occurs by free convection. With conduction terms the resistance varies linearly with the distance. In free convection, however, the resistance term is dependent on the temperature difference and on the dimensions of the cavity. Over the practical range of interest it is apparent that these effects cancel each other out.

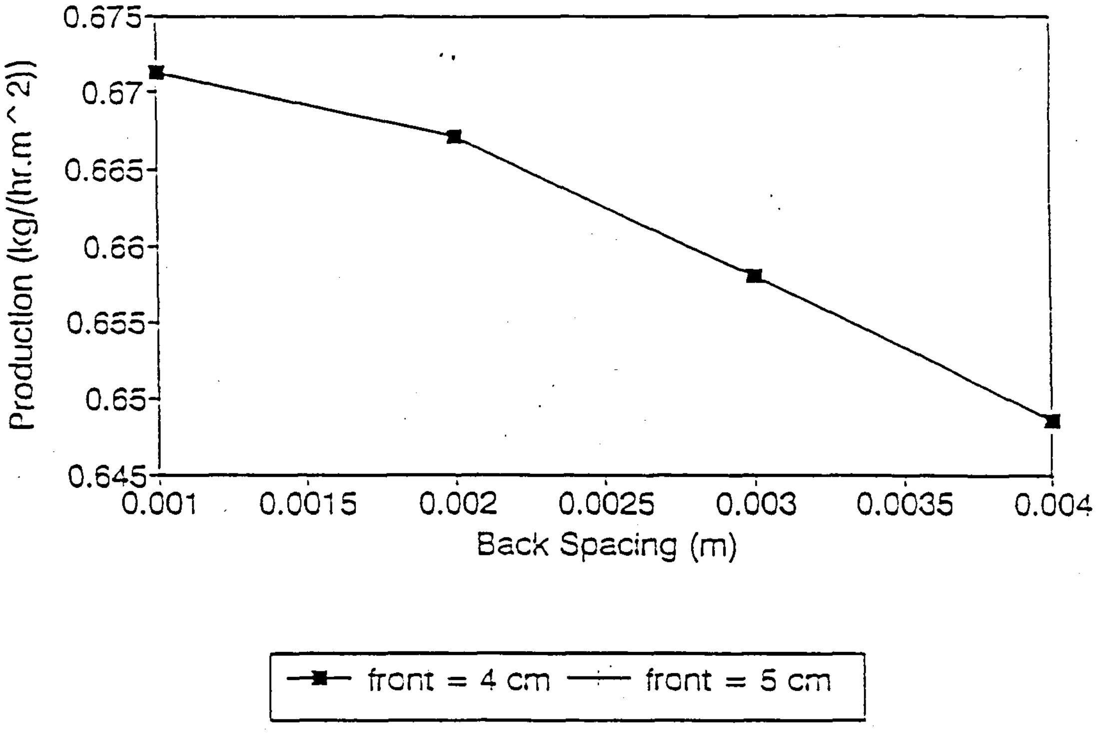

Figure 4.12 : Membrane Bag : Spacing Effect.

4.2.2 DOUBLE-EFFECT UNIT

Results are shown in Tables 13 to 20 in Appendix 2.

Figs. 4.13 to 4.18 show the various effects of the environmental and design variables on the double-effect unit, and the trends are the same as those discussed for the single-effect unit.

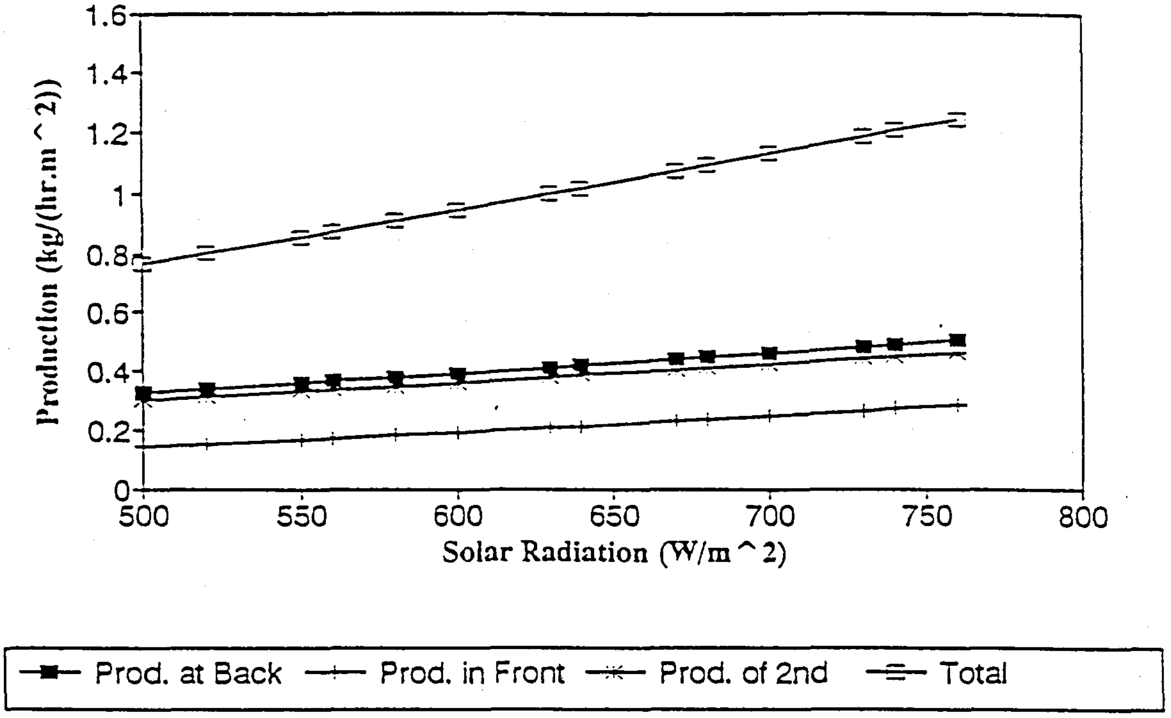

Figure 4.13 : Membrane Bag : Production vs. Radiation.

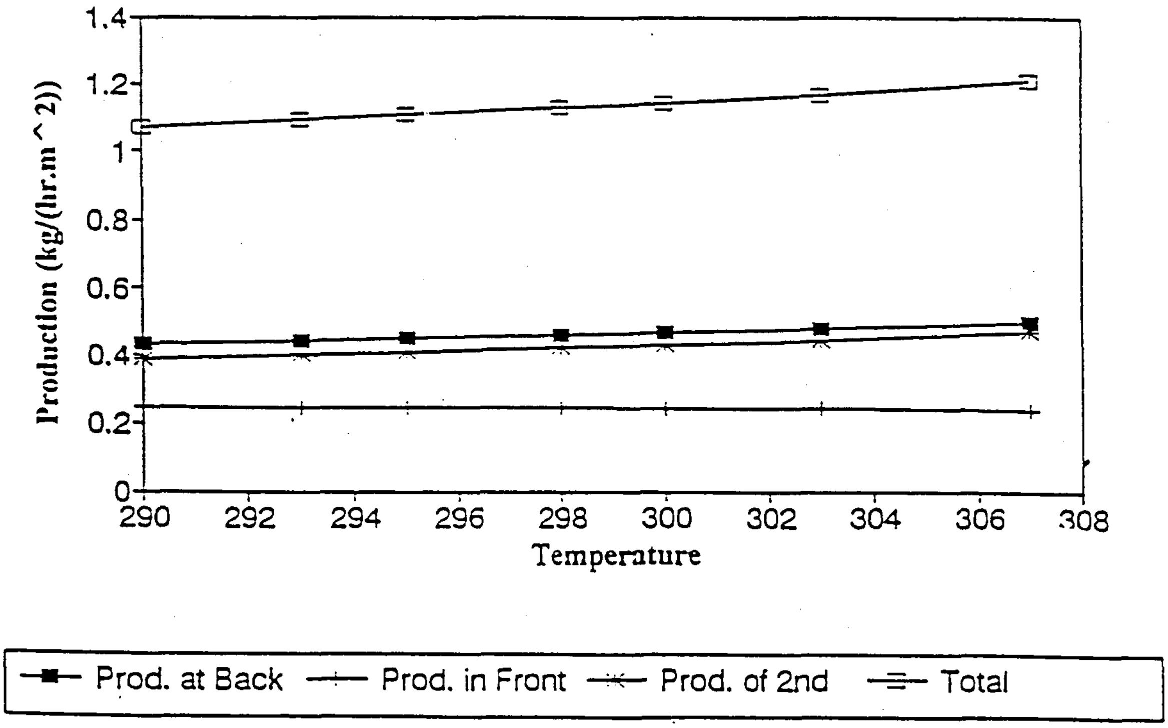

Figure 4.14 : Membrane Bag : Production vs. Ambient Temperature.

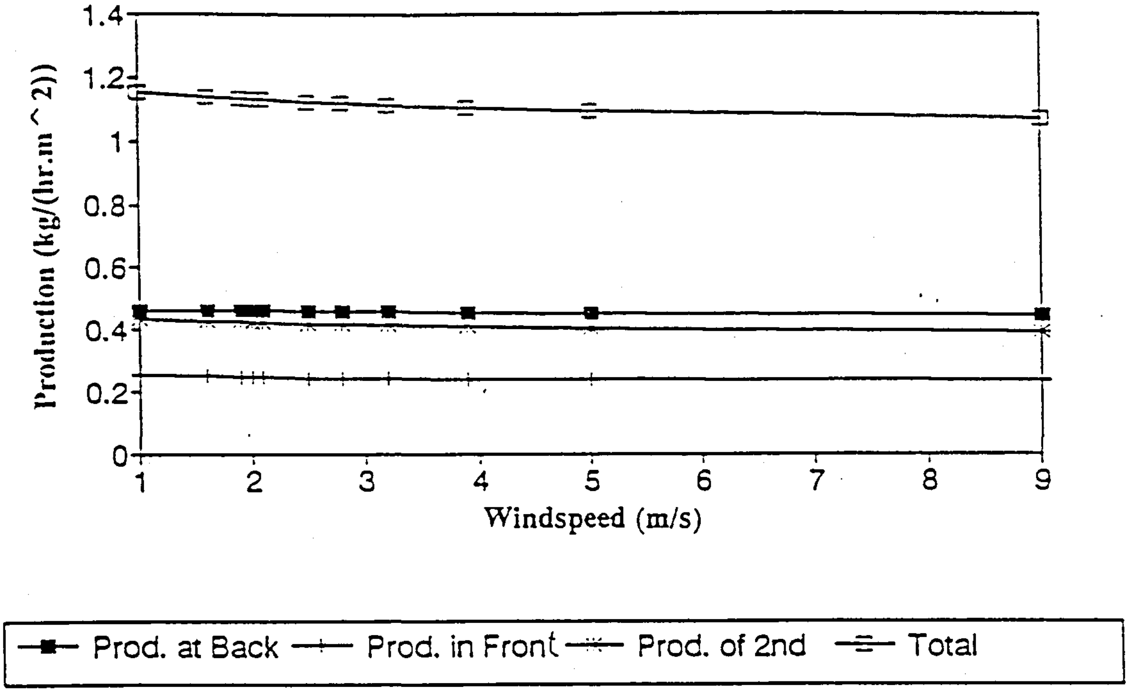

Figure 4.15 : Membrane Bag : Production vs. Windspeed.

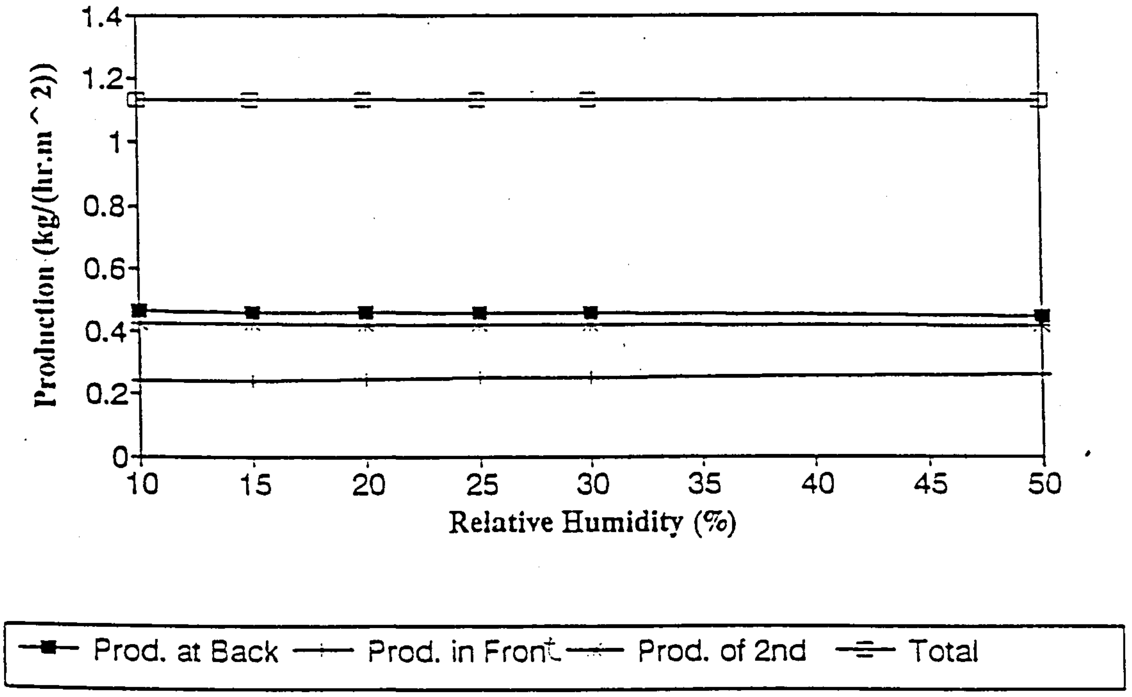

Figure 4.16 : Membrane Bag : Production vs. Relative Humidity.

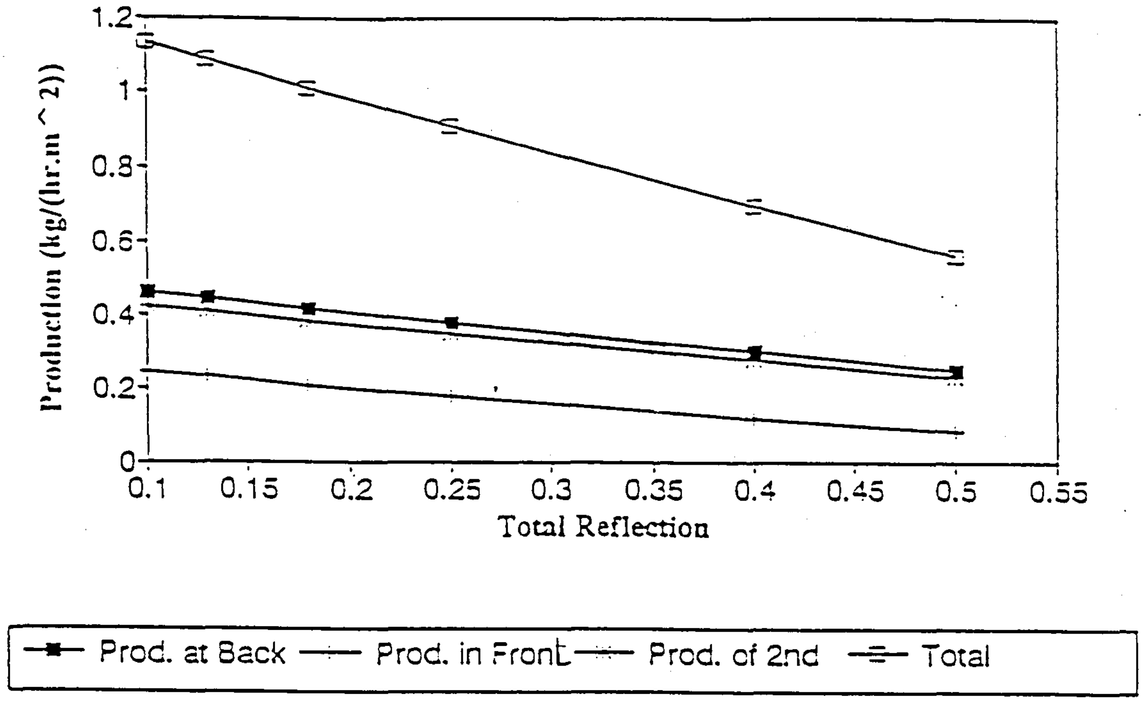

Figure 4.17 : Membrane Bag : Production vs. Reflection.

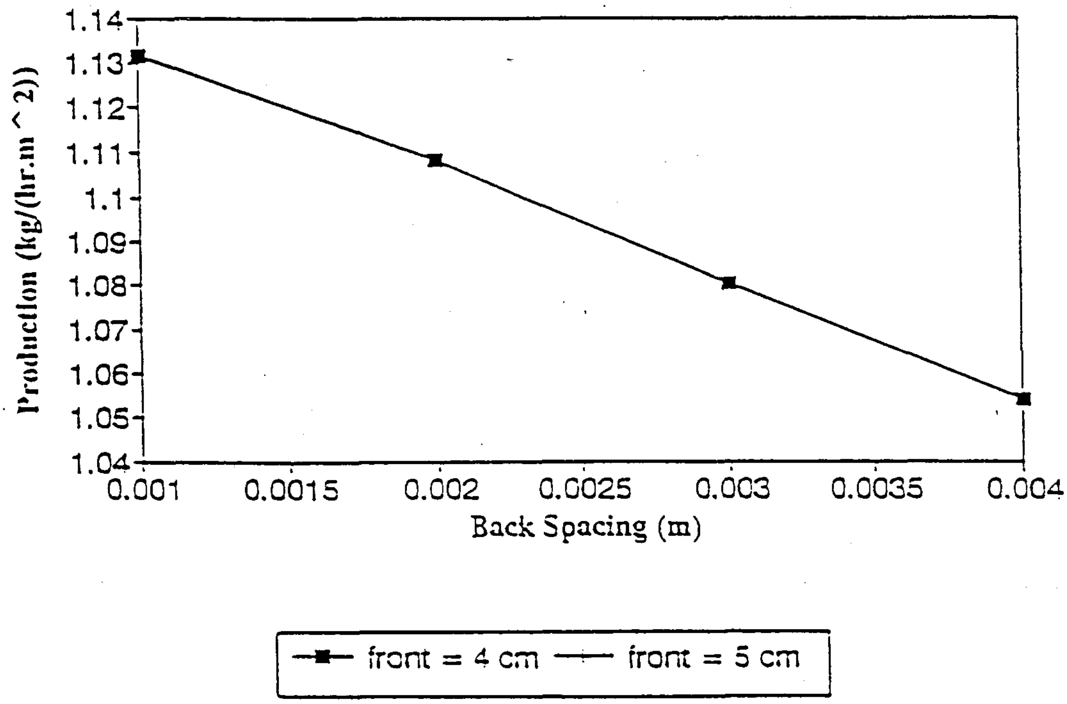

Figure 4.18 : Membrane Bag : Spacing Effect.

4.2.3 COMPARISON BETWEEN SINGLE-EFFECT AND DOUBLE-EFFECT UNITS

Figs. 4.19 to 4.23 show the comparisons between the productivities of the single- and the double-effect systems. The double-effect system has a much higher production than the single effect (60%). This is because the heat is re-used for evaporation at an extra surface. Theoretically it should be possible to have a triple-effect system or higher but due to construction difficulties this would be very difficult.

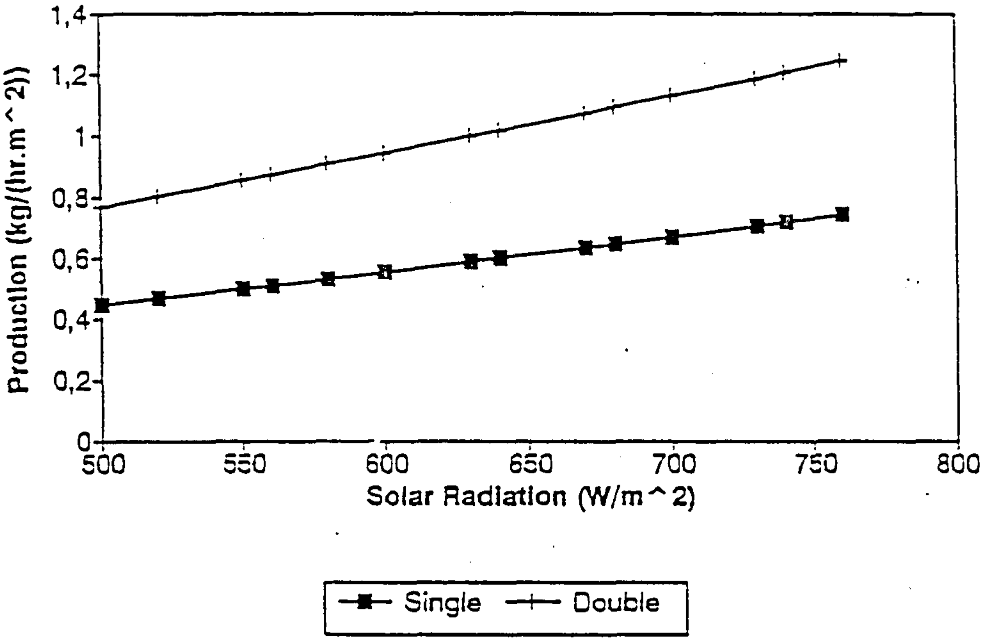

Figure 4.19 : Total Production vs. Radiation.

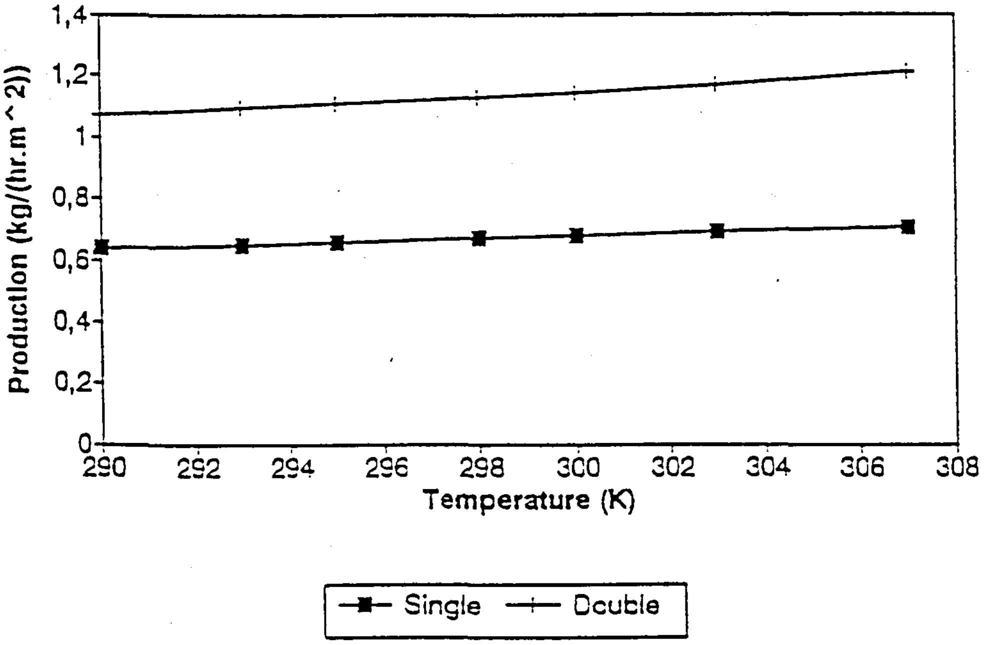

Figure 4.20 : Total Production vs. Ambient Temperature.

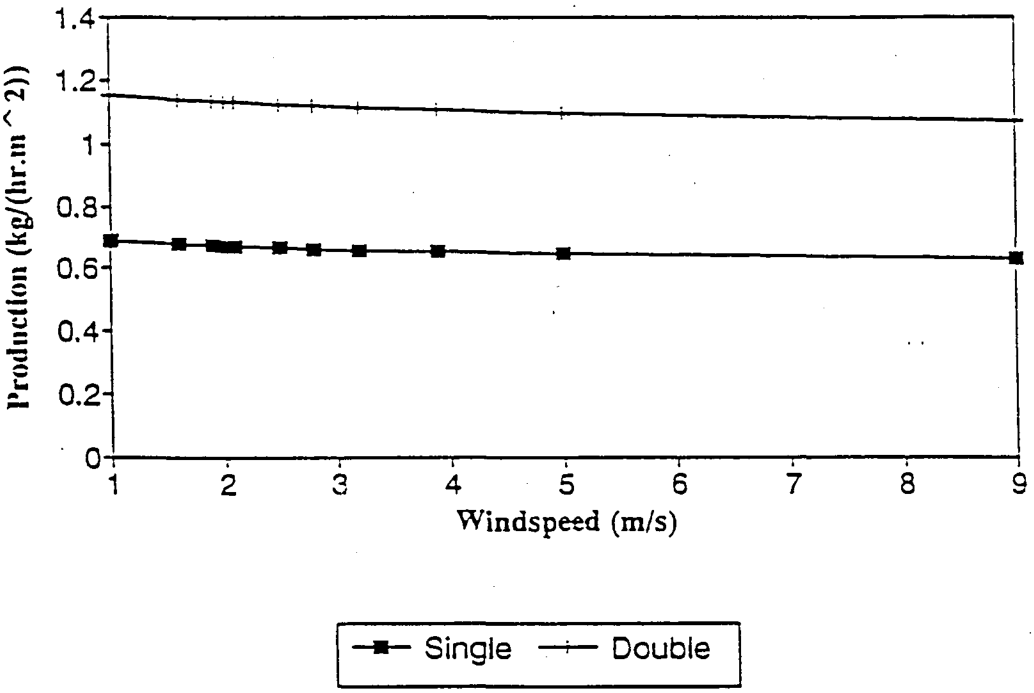

Figure 4.21 : Total Production vs. Windspeed.

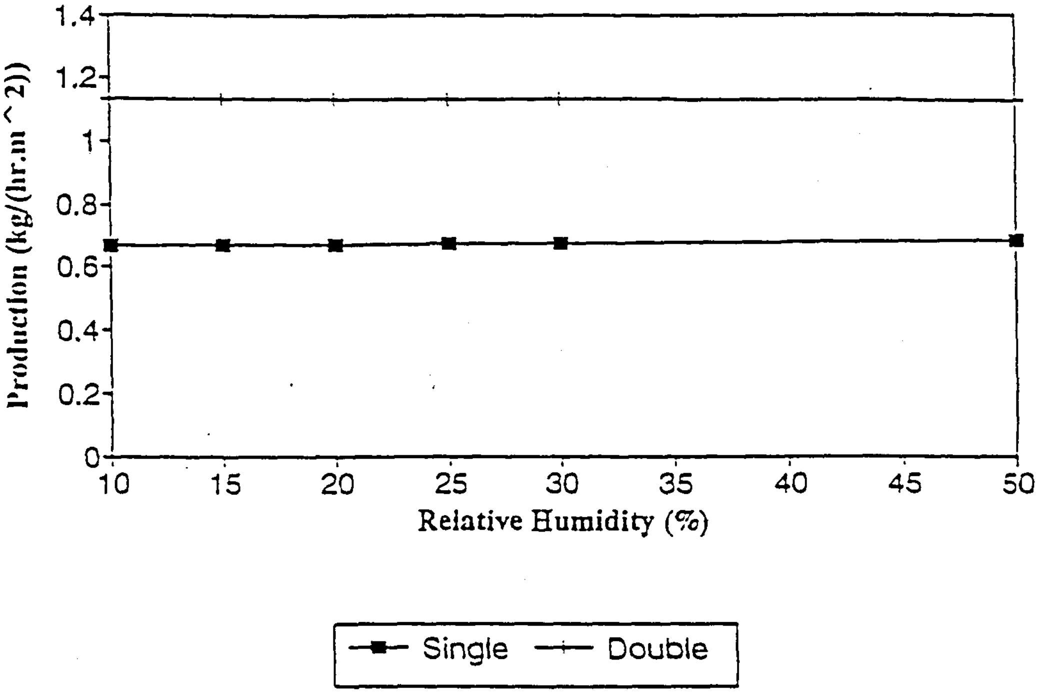

Figure 4.22 : Total Production vs. Relative Humidity.

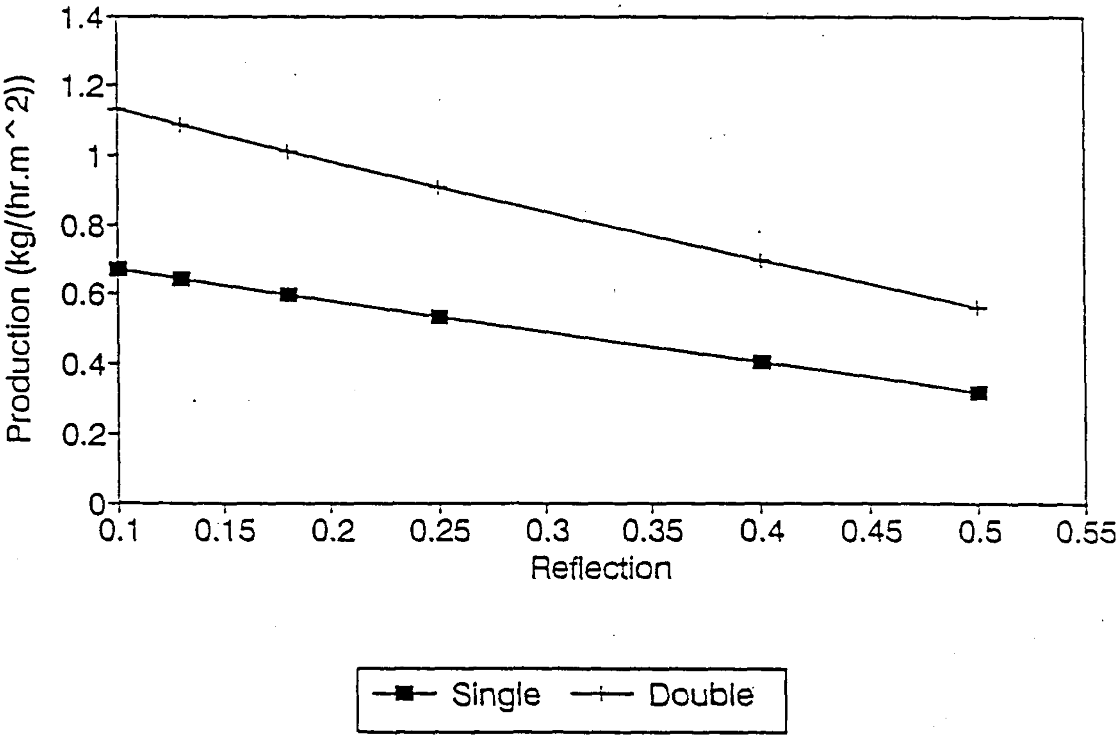

Figure 4.23 : Total Production vs. Reflection.

The simulation was also done with a flow rate of 10 ℓ/h compared with the standard value of 5 ℓ/h. The only difference found was a slight decrease in the production rate (from 0,671 kg/(h.m2) to 0,656 kg/(h.m2)). This was because the operating temperature of the unit was slightly lower because the temperature of the water inlet to the unit from the preheater was lower.

4.3 EXPERIMENTAL UNIT

The following results were obtained from the experimental unit, at steady state, and compared with those of the computer simulation:

Table 4.1 : Comparison between experimental unit and computer simulation.

WATER TEMP (°C)	EXP. PRODUCT [kg/(h.m2)]	SIM. PRODUCT [kg/(h.m2)]
45	0,272	0,175
50	0,312	0,264
55	0,348	0,292

Because of experimental difficulties concerning the membrane bag, only these results could be obtained. The experimental production rate was higher than the results obtained in the simulation. A possible explanation could be that there was a greater difference between the temperature of the water inside the bag and that of the outside condensing surface, which created a higher evaporation driving force in the front cavity. This was because solar radiation was not absorbed by the clear cover, which in turn created the higher temperature difference with the indoor unit. It should be noted that there was, at this stage, a considerable difference between the results obtained with the experimental unit and the simulation unit, and for this reason no final conclusions can be drawn as to how closely the two models compare.

5. CONCLUSIONS ON THE INITIAL EXPERIMENTAL WORK

The results of this study show that the solar still can be modelled using conventional heat-transfer theory. The environmental factors that lead to higher production rates are those that result in a higher operating temperature. These are: wind speed, high radiation levels and a high ambient temperature. The most important of these is the solar radiation since it determines the energy input. The other factors simply influence the way the energy is transported from the collecting surface to the environment.

The design aspects of the unit that can be adjusted to give high productivity are:

i. a large number of stages;
ii. the use of evaporative cooling to promote heat re-use;
iii. a collector with a low reflectivity; and
iv. a small diffusion gap.

The front gap size did not have a significant influence. Again the major influences were those aspects that determine the energy input to the system.

6. FURTHER EXPERIMENTAL WORK

6.1 MODELLING THE PROCESS

The initial model, in the form of a computer program was developed with the aim of testing such a model against the experimental results. From the modelling of the process it was clear that a large number of variables would influence the final result, namely, the rate of production of potable water. Factors which are most likely to influence the production rate are:

i. the amount of solar energy in the form of radiation which is received by the experimental system;
ii. the temperature of the water which is fed to the system;
iii. ambient temperature;
iv. windspeed; and
v. the reflection and absorption of sunlight.

Another important factor is the thickness of the spacer material between the membrane and the surface upon which the vapor condenses.

The theoretical model comprises mass and energy balances and uses appropriate correlations for the heat transfer, diffusion rate of the vapor, as well as for the heat generated by the condensation of the vapor. Models for both the single- and double-effect systems were developed, making it possible to determine the influence and importance of the different variables on the distillation process.

6.2. EXPERIMENTAL

Canvas was used to make the membrane bag for the first experimental model. This was, however, not satisfactory because the canvas was not strong enough to withstand the pressure from the water inside the bag. The idea of heating a membrane bag, with production on both the front and the back sides of the bag, was abandoned because an exceptionally strong material would be required to withstand the direct sunlight.

A second experimental model was built, using an anodized aluminium plate to absorb the solar heat. The water was placed between the plate and the membrane, to allow the water to be heated by the plate. Experiments carried out in direct sunlight showed that the temperature of the black aluminium plate rose to above 80°C. Although this experiment was carried out in direct sunlight, there was also a great deal of heating by radiation, so that it would be possible to operate the distillation unit on cloudy days.

A variety of problems, with leakage being one of the most serious, made it necessary to build a third model. The third model had the advantage that different membranes could be tested without the need to build a new model for each new membrane, as was the case with the previous models.

Although this third model modelled only a single effect, it produced helpful test results. The heating of the water by sunlight was simulated by means of a heating element in the laboratory.

Two pumps were used to circulate the heated water, as well as the cooling water which was necessary to keep the condensing surface at a specified temperature.

6.3 RESULTS

The preliminary tests produced some results on the production rate of potable water as a function of the temperatures of the heated water, and the cooling water.

Two types of membranes were tested, one with a material cloth on both sides of the membrane to protect it, and the other with a cloth on only one side of it.

In the first experiment the temperature of the cooling-water was kept constant at 14°C, and that of the heated-water was varied. This experiment was conducted using the membrane with the cloth on both sides.

Table 6.1 : Membrane 1 : Cooling-water temperature constant (14°C).

HEATED-WATER TEMP. (°C)	PRODUCTION RATE [mℓ/(h.m2)]
50	74,1
54	78,0
60	160,7
62	183,5
65	192,7
76	330,3

In the second experiment the influence of the cooling water temperature (condensing surface) was investigated, keeping the heated water at a constant temperature of 65°C.

Table 6.2 : Membrane 1 : Heated-water temperature constant (65°C).

COOLING-WATER TEMP. (°C)	PRODUCTION RATE [mℓ/(h.m2)]
13	204,5
15	192,7
19	183,5

The second membrane (with protecting cloth on only one side) was tested to determine whether the cloth had any influence on the diffusion rate of vapor through the membrane. The temperature of the cooling water (and thus of the condensing surface) was again kept constant at 14°C.

Table 6.3 : Membrane 2 : Cooling-water temperature constant (14°C).

HEATED-WATER TEMP. (°C)	PRODUCTION RATE [mℓ/(h.m2)]
48	517,1
57	587,2
61	652,4
64	764,3

In these tests with the cloth on only one side of the membrane, a sodium chloride (NaCl) solution of 2 000 ppm was used to ensure that there were no leaks in the membrane. The concentration of NaCl in the permeate, varied from 250 to 400 ppm. This gave percentage retentions of about 85% up to 90%.

The influence of the cooling-water temperature on the permeate production rate was tested in one experiment in which the temperature of the cooling water was kept constant at 40°C. With the temperature of the heated-water at 65°C, the permeate production rate was 0,876 ℓ/(h.m2). This higher production rate at a higher cooling-water temperature will be very useful when a model which consists of more than one stage, is built. This higher cooling-water temperature can be used with a second stage, when the production rate may be small, but can favorably influence the production rate in the first stage of the solar distillation unit.

6.4 DISCUSSION OF RESULTS

The above results show that the protecting cloth has a definite influence on the rate of diffusion of the vapor to the condensing plate. Ideally, it would be best to use a membrane without a cloth, but the membrane would be damaged too easily, which would result in leakages of non-potable water onto the condensing surface. The Teflon membrane with cloth proved to be the best option, because reasonable protection of the membrane could be obtained and a high production rate of potable water was achieved.

The results confirm the idea that the temperature of the heated water plays the most important role in the rate of production of permeate. On thermodynamic grounds the amount of vapor that is formed would increase if the temperature of the heated water was increased.

The temperatures at which condensation occurs do not play an important role in the amount of permeate formed. This factor may be an important variable when more than one stage is built into the testing model.

One of the factors that influences the permeate production rate considerably, but which cannot be measured directly, is the flow pattern in the heated water. The ideal would be to provide channels to ensure that only a small layer of heated water is in contact with the membrane and to ensure optimum vaporization and diffusion through the membrane. Without certain forced-flow patterns, stagnant volumes of water are formed, which have a negative influence on the efficiency of the model.

The most important changes to the current model would be to provide the system with more than one stage, using the heat that is generated when vapor is condensed, and a change in materials to give a more versatile and compact model. In the laboratory tests, electrical pumps are used to circulate the water. The ideal would be to use solar pumps to circulate the water, which would result in a model that could be used in almost any circumstances.

6.5 COMPARISON BETWEEN THE MATHEMATICAL MODEL AND THE EXPERIMENTAL RESULTS

The model that was developed was for a membrane bag with vapor which leaves the bag at the front and at the back. The idea of a bag was subsequently abandoned, which made it necessary to change the model accordingly.

With the current model, vapor is formed only at the side opposite to that on which the heating takes place. The model should therefore be changed accordingly to accommodate this modification.

An in-house poster of D.W. Schoeman is included in Appendix 3.

7. RECOMMENDATIONS

The concept of evaporation through a microporous membrane by means of solar energy has been demonstrated, but several aspects of the project require further development. These include:

i. coupling of the evaporative cooling surface to the unit;
ii. the use of multiple stages;
iii. the testing of different varieties of membranes;
iv. economic optimization; and
v. field testing.

The point regarding membrane development applies to the field of membrane distillation in general. Microporous membranes have been shown to become wet after a period of time in contact with water containing high concentrations of saturated salts. It is possible to pre-treat water before distillation, but this generally retards rather than prevents the wetting process.

The sizes of the components used would have an effect on the unsteady-state operation of the unit. In particular the mass of water held in the system would affect the time required for the unit to reach equilibrium. This must be examined in the final optimization of the unit.

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```
program maxsin;
uses crt,printer;

const
ec1 = 0.94;      {Emmisitivity of the plastic cover}
ec2 = 0.94;      {Emmisitivity of the plastic cover}
alcs = 0.04;     {Absorptivity of the cover}
de = 0.04;       {Depth of evaporator bag}
ecb =  0.9;      {Emmivity of bag}
b =  0.0002;     {Membrane thickness}
sig = 0.8;        {Porosity of membrane}
ec = 0.94;        {Emmitivy}
Bi = 1.388E-3;    {Flowrate of water [kg/s]}
Cp = 4180;
Ac1p = 1.01;
Ac2p = 1.01;
Abag = 1.01;
Aw = 1.01;
Ac = 1.01;
Ma = 18;          {Molecular weight [kg/kmol]}
hfg = 2450000;    {Evaporation heat [J/kg] }
R = 8315;         {Gas constant [J/mol.K] }
rho = 1.16;       {Density [kg/m^3] }
cpa = 1007;       { J/kg.K }
Le = 0.769;       { Outside Lewis number }
Le2 = 0.9231;     {Inside Lewis number }
Fak = 1;          { J/Nm}
A1 = 23.238;      {Antionne constants }
B1 = 3841;
C1 = 45;
Acb = 1.01;
kw = 27E-3;       {W/m.K}
eb1 = 0.9;
hfg2 = 2440000;    {J/kg}
Pt = 101325;       {Atmospheric pressure [Pa]}
Abag1 = 1.01;
hfg3 = 2350000;
eb =  0.94;
hfg4 = 2366000;

var
f  :    text;
name : string[20];
GG : char;
Tbmin,Tbmax,Antwoord,Ts,verg4,hwp,Ant,Tcp1,Tcp2,Tcp1max,Tcp1mi
n,Th,
D1,hi,Tc,Tw,Ts1,T1max,T1min,T1,Tb,Tb2,Tw2,Tw1,Tbag,Tb1,D2,D3,V
erg5 : real;
Tb3,D4,Io,dp,xw,Ta,u,er,u2,hum : real;

procedure constants;
var
place : integer;
c: array[0..20] of real;
store : text;

function tester (message:string; value : real):real;
var
```

```
  code : integer;
  answr : real;
  input : string[20];

  begin
    write(message,’ (’,value:0:5,’):’);
    readln(input);
      if input = ’’ then
      tester := value
    else
     begin
       val(input,answr,code);
       Tester := Answr;
     end;
    writeln;
  end;

  begin
    Assign (Store, ’a:cnstnts’);
    reset(store);
      for place := 0 to 20 do
        readln(store,c[place]);
    close(store);
    clrscr;
    writeln(’Single effect solar distiller input variables’);
    writeln;
    c[0] := Tester (’Radiation(Io (W/m^2))’,c[0]);
    c[1] := Tester (’ Ambient Temperature(Ta(xK))’,c[1]);
    c[2] := Tester (’Windspeed in front(u (m/s))’,c[2]);
    c[3] := Tester (’ Total reflection(er)’,c[3]);
    c[4] := Tester (’Windspeed at back(u2(m/s)’,c[4]);
    c[5] := Tester (’ Relative humidity(hum)’,c[5]);
    c[6] := Tester (’Front spacing(dp(m))’,c[6]);
    c[7] := Tester (’ Back spacing(xw(m))’,c[7]);
    Assign(store,’a:cnstnts’);
    Rewrite (store);
      for place := 0 to 20 do
        writeln(store,c[place]);
    close(store);
    assign(store,’a:cnstnts’);
    reset(store);
    readln(store,Io);
    readln(store,Ta);
    readln(store,u);
    readln(store,er);
    readln(store,u2);
    readln(store,hum);
    readln(store,dp);
    readln(store,xw);
    close(store);
 end;

{Start of preheater calculations}

 procedure Tcover2;
 var
   sum1,sum2,sum3,sum4,Tcp2max,Tcp2min : real;
  begin
```

```
      Tcp2max :=350;
      Tcp2min := 270;
        repeat
          Tcp2:= (Tcp2max + Tcp2min)/2;
           if Tcp1 < Tcp2 then
           Tcp2 := Tcp1 - 1
           else
           Tcp2 := Tcp2;
                  sum1 := Io*alcs +
ac1p*5.67E-8*ec1*(exp(4*ln(Tcp1))-exp(4*ln(Tcp2)));
                               sum2 :=
0.787/dp*exp(0.31*ln(dp*dp*dp*(Tcp1-Tcp2)))*(Tcp1-Tcp2)*Ac1p;
       sum3 := -Ac2p*(3.903*sqrt(u)*(Tcp2-Ta)+
                5.67E-8*(exp(4*ln(Tcp2))-exp(4*ln(Ts)))*ec2);
       sum4 := sum1 + sum2 +sum3;
         if sum4 > 0 then
           Tcp2min := Tcp2
         else
          if sum4 < 0 then
           Tcp2max := Tcp2
        until (sum4 > -0.001) and (sum4 < 0.0001);
   end;

procedure Thot;

const
      Tref = 273.16;     {Reference temperature}
      Tinlet = 293.15;

var
   som1,som2,som3,Thmin,Thmax : real;
   begin
     Thmin :=270;
     Thmax :=1000;
       repeat
         Th := (Thmin + Thmax)/2;
              som1 := -Bi*cp*Tinlet/Ac2p +
Bi/Ac2p*cp*(2*Th-Tinlet)-Io*(1-er);
         som2 := Ac2p*(3.903*sqrt(u)*(Tcp2-Ta)+5.67E-8*ec2*
         (exp(4*ln(Tcp2))-exp(4*ln(Ts))));
         som3 := som1 + som2;
          if som3 <0 then
             Thmin := Th
           else
             if som3 > 0 then
                Thmax := Th;
       until (som3 < 0.0001) and (som3 > -0.0001);
    end;

procedure bag;

  const  alcs2 = 0.04;
       k = 650E-3;
       x = 0.07;
       Nu = 4.558;
       Pi = 3.1415;
  var
    Tbagmin,Tbmax : real;
```

```
  begin
    hwp := Nu*k/(4*0.1156*Pi*x/(2.3/5));
    Tbag := (Io*(1-(alcs+alcs2))+Th*hwp*Abag)/hwp/Abag;
  end;

procedure check;
  var
     verg1,verg2,verg3 : real;
  begin
    verg1 := hwp*(Th-Tcp1)*Abag+Io*(1-alcs)*alcs;
                    v    e    r    g    2              :    =
-Ac1p*(Tcp1-Tcp2)*0.787/dp*exp(0.31*ln(dp*dp*dp*(Tcp1-Tcp2)));
    verg3 := -Ac1p*5.67E-8*ec1*(exp(4*ln(Tcp1))-exp(4*ln(Tcp2)));
    verg4 := verg1 + verg2 + verg3;
  end;

procedure output1(name:string);
  begin
    WriteLn(f,'non-ideal situation');
    WriteLn(f,'Radiation',Io:0:4);
    WriteLn(f,'Amb.temp',Ta:0:4);
    WriteLn(f,'Windspeed',u:0:4);
    WriteLn(f,'Reflection',er:0:4);
    WriteLn(f,'Relative humid',hum:0:4);
    WriteLn;
    WriteLn(f,'dp =', dp:0:5);    {for sensitivity study}
    WriteLn(f,'xw =', xw:0:5);
    WriteLn(f,'Temperature of outside cover ',Tcp2:7:3,' K);
    WriteLn(f,'Temperature of inside cover ',Tcp1:7:3,' K);
    Writeln(f,'Temperature of the water ,'Th:7:3,' K');
    WriteLn(f,'Temperature of the bag ,'Tbag:7:3,' K');
  end;

  {Start of membrane bag calculations}

procedure evap;  {Balance around T1}
  var
    sum5,Ts1min,Ts1max,sum1,sum2,sum3,sum4 : real;
  begin
  Ts1min := T1;
  Ts1max := 330;
   Repeat
    Ts1 := (Ts1min + Ts1max)/2;
    sum1 := -3.908*sqrt(u2)*(Ta-T1)*Acb-5.67E-8*ecb*Acb*
         (exp(4*ln(Ts))-exp(4*ln(T1)));
                      s    u    m    2                     :    =
-0.613/de*(0.292+132*exp(0.327*ln(de*de*de*(Ts1-T1))))*(Ts1-T1);
                      s    u    m    3                     :    =
Ma*hfg*3.908*sqrt(u2)*fak/(R*rho*cpa*(exp(2/3*ln(Le))))
         *(exp(A1-B1/(T1-C1))/T1-Hum*exp(A1-B1/(Ta-C1))/Ta);
    sum4 := sum1 + sum2 + sum3;
      if sum4 < 0 then
           Ts1max := Ts1
            else
      if sum4 > 0 then
           Ts1min := Ts1;
   until (sum4 > -0.00001) and (sum4 < 0.00001);
  end;
```

```
procedure evap2;  {Balance around Ts1}
 var
   Tb1min,Tb1max,sum1,sum2,sum3,sum4 : real;
   begin
     Tb1min := 290;
     Tb1max := 400;
       repeat
        Tb1 := (Tb1min + Tb1max)/2;
                                       sum1 :=
-kw/xw*(Tb1-Ts1)*Aw-Abag1*5.67E-8*(exp(4*ln(Tb1))-exp(4*ln(Ts1
)))*eb1;
                                                  sum2
:=0.613/de*(0.292+132*exp(0.327*ln(de*de*de*(Ts1-T1))))*(Ts1-T1);
                                       sum3 :=
-1.138E-6*hfg2*1/(b/(sig*sqrt(Tb1))+xw/sqrt(Ts1))*ln
        ((1-exp(A1-B1/(Ts1-C1))/Pt)/(1-exp(A1-B1/(Tb1-C1))/Pt));
        sum4 := sum1 + sum2 +sum3;
        if sum4 > 0 then
          Tb1min := Tb1
          else
        if sum4 < 0 then
          Tb1max := Tb1;
      until (sum4 <0.0001) and (sum4 > -0.0001);
   end;

procedure Evap3;  {Balance around Tb1}
  var
    Twmin,Twmax,sum1,sum2,sum3,sum4 : real;
  begin
    Twmin := Tb1;
    Twmax :=400;
       repeat
      Tw := (Twmin + Twmax)/2;
                                   sum1 :=
Aw*kw/xw*(Tb1-Ts1)+Abag1*eb1*5.67E-8*(exp(4*ln(Tb1))-
         exp(4*ln(Ts1)));
      D4 := 1.138E-6*hfg3*1/(b/(sig*sqrt(Tb1))+xw/sqrt(Ts1))*ln

((1-exp(A1-B1/(Ts1-C1))/Pt)/(1-exp(A1-B1/(Tb1-C1))/Pt));
      sum3 := -hwp*(Tw-Tb1)*Aw;
      sum4 := sum1 + D4 + sum3;
       if sum4 > 0 then
         Twmin := Tw
          else
        if sum4 < 0 then
           Twmax := Tw
      until (sum4 < 0.0001) and (sum4 > -0.0001);
   end;

procedure extra; {Balance to calculate Tw}
  var
    sum1,Tbmin,Tbmax : real;
   begin
        Tbmin := Tw;
        Tbmax := 370;
     repeat
       Tb := (Tbmin + Tbmax)/2;
       sum1 := Aw*hwp*(Tb-Tw)-Aw*hwp*(Tw-Tb1);
```

```
       if sum1 < 0 then
        Tbmin := Tb
          else
       if sum1 > 0 then
        Tbmax := Tb;
     until (sum1 < 0.0001) and (sum1 > -0.0001);
   end;
{
procedure dubbel;
  var
    Tb2max,Tb2min,sum1,sum2,sum3,sum4 : real;
  begin
    Tb2min := 290;
    Tb2max := 400;
     repeat
       Tb2 := (Tbmin + Tbmax)/2;
                                sum1 :=
-kw/xw*(Tb2-Tb)*Aw-Abag1*5.67E-8*(exp(4*ln(Tb2))-exp(4*ln(Tb))
)*eb1;
       sum2 := Aw*hwp*(Tb-Tw);
       sum3 :=-1.138E-6*hfg2*1/(b/(sig*sqrt(Tb2))+xw/sqrt(Tb))*

ln((1-exp(A1-B1/(Tb-C1))/Pt)/(1-exp(A1-B1/(Tb2-C1))/Pt));
       sum4 := sum1 + sum2 + sum3;
        if sum4 > 0 then
         Tb2max := Tb2
           else
        if sum4 < 0 then
          Tb2max := Tb2;
     until ( sum4 < 0.0001) and (sum4 > -0.0001);
  end;


procedure dubbel2;  {Balance aroundTb2}
  var
    Tw1max,Tw1min,sum1,sum2,sum3,sum4 : real;
  begin
    Tw1min := Tb2;
    Tw1max := 400;
     repeat
       Tb1 := (Tw1min + Tw1max)/2;
                                sum1 :=
Aw*kw/xw*(Tb2-Tb)-Abag1*eb1*5.67E-8*(exp(4*ln(Tb2))-exp(4*ln(T
b)));
       sum2 := Aw*hwp*(Tb-Tw);
       sum3 := 1.138E-6*hfg3*1/(b/(sig*sqrt(Tb2))+xw/sqrt(Tb))*

ln((1-exp(A1-B1/(Tb-C1))/Pt)/(1-exp(A1-B1/(Tb2-C1))/Pt));
       sum4 := sum1 + sum2 + sum3;
        if sum4 > 0 then
         Tw1min := Tw1
           else
        if sum4 < 0 then
          Tw1max := Tw1;
     until ( sum4 < 0.0001) and (sum4 > -0.0001);
  end;

procedure dubbel3;  {Balance around Tw1}
```

```
  var
    Tb3max,Tb3min,sum1 : real;
  begin
    Tb3min := Tw1;
    Tb3max := 380;
     repeat
       Tb3 := (Tb3min + Tb3max)/2;
       sum1 := Aw*hwp*(Tb3-Tw1) - Aw*hwp*(Tw1-Tb2);
       if sum1 < 0 then
         Tb3min := Tb3
           else
        if sum1 > 0 then
          Tb3max := Tb3;
     until ( sum1 < 0.0001) and (sum1 > -0.0001);
  end;
 }

procedure check1;
var
  Tcmin,Tcmax,sum1,sum2,sum3 : real;
  begin
    Tcmin := 290;
    Tcmax := Tb;
   repeat
    Tc := (Tcmin + Tcmax)/2;
    hi := 0.787/dp*exp(0.31*ln(dp*dp*dp*(Tb-Tc)));
                            D1 :=
Ma*hi/(R*rho*cpa*exp(2/3*ln(Le2)))*(exp(A1-B1/(Tb3-C1))/Tb-
    exp(A1-B1/(Tc-C1))/Tc);
    sum1 := hi*(Tb-Tc)+Io*alcs+D1*hfg4+Aw*eb*5.67E-8*
            (exp(4*ln(Tb))-exp(4*(Tc)));
   sum2 :=-Ac*(3.908*sqrt(u)*(Tc-Ta)+5.67E-8*ec*(exp(4*ln(Tc))-
            exp(4*ln(Ts))));
   antwoord := sum1 + sum2;
     if antwoord > 0 then
         Tcmin := Tc
           else
     if antwoord < 0 then
         Tcmax := Tc;
    until (antwoord > -0.0001) and (antwoord <0.0001);
  end;

procedure check2;
var
   Verg1,verg2,verg3 : real;
    begin
     D2 :=  1.138E-6*1/(b/(sig*sqrt(Tb1))+xw/sqrt(Ts1))*

ln((1-exp(A1-B1/(Ts1-C1))/Pt)/(1-exp(A1-B1/(Tb1-C1))/Pt));
     Verg1 := -Io*(1-er)+(D1+D2)/Ac*Cp*((Tc+Ts1)/2)
               -Bi*Cp/Ac*Th+(Bi-D1-D2)/Ac*Cp*Th;
                         Verg2 :=
Ac*(3.908*sqrt(u)*(Tc-Ta)+5.67E-8*ec*(exp(4*ln(Tc))-

exp(4*ln(Ts))))-5.67E-8*Acb*ecb*(exp(4*ln(Ts))-exp(4*ln(T1)));
                         Verg3 :=
Ma*hfg*3.908*sqrt(u2)/(R*rho*cpa*(exp(2/3*ln(Le))))*
              (exp(A1-B1/(T1-C1))/T1-hum*exp(A1-B1/(Ta-C1))/Ta)*
```

```
                -3.908*sqrt(u2)*(Ta-T1)*Acb;
         Verg5 := Verg1 + Verg2 + Verg3;
        end;

    procedure output2(name:string);
    begin
         WriteLn(f);
         WriteLn(f,'     Membrane bag calculations');
         WriteLn(f);
         WriteLn(f,'     T1 = ',T1:7:3,' K');
         WriteLn(f,'     Ts1 = ',Ts1:7:3,' K');
         WriteLn(f,'     Tb1 = ',Tb1:7:3,' K');
         WriteLn(f,'     Tw = ',Tw:7:3,' K');
         WriteLn(f,'     Tb = ',Tb:7:3,' K');
         WriteLn(f,'     Tc = ',Tc:7:3,' K');
         WriteLn(f);
         WriteLn(f,'Prod at back = ',D2:0:5,' kg/hr.m^2');
         WriteLn(f,'Prod  at  back  of  second  bag  =  ',D4:0:5,'
    kg/hr.m^2');
         WriteLn(f,'Total production = ',D3:0:5,' kg/hr.m^2');
    end;

    procedure choice;
    var
    dev : char;
    device : string[4];

     begin
       WriteLn(' Please select option ');
       WriteLn;
       WriteLn(' Printer or screen (P/S)');
       Dev := Readkey;
       if upcase(dev) = 'S' then
       name := 'con'
        else
        name := 'lpt1';
      end;

      begin
       constants;
       ClrScr;
       Tcp1min := 310;
       Tcp1max := 393;
       Ts :=Ta - 6;
         repeat
          WriteLn('      Wait    ');
           Tcp1 := (Tcp1max + Tcp1min)/2;
           Tcover2;
           Thot;
           Bag;
           check;
            if verg4 < 0 then
              Tcp1max := Tcp1
               else
                 Tcp1min := Tcp1;
                 ClrScr;
         until (verg4 < 0.0001) and (verg4 > -0.0001);
           choice;
```

```
      ClrScr;
      Assign(f,name);
      Rewrite(f);
      output1 (name);
      T1min := 290;
      T1max := 320;
    repeat
      T1 := (T1min + T1max)/2;   {Choose initial value for T1}
      evap;
      evap2;
      evap3;
      extra;
      check1;
      check2;
     if verg5 < 0 then
       T1min := T1
     else
     if verg5 > 0 then
       T1max := T1;
    until (verg5 <0.0001) and (verg5 > -0.0001);
      D3 := (D2 + D4)/3600;
      D2 := D2*3600;
      D4 := D4/3600;
      output2(name);
      close(f);
      GG := ReadKey;
end.
```

```
program Maxdubb;
uses crt,printer;

const
ec1 = 0.94;      {Emmisitivity of the plastic cover}
ec2 = 0.94;      {Emmisitivity of the plastic cover}
alcs = 0.04;     {Absorptivity of the cover}
de = 0.04;       {Depth of evaporator bag}
ecb =  0.9;      {Emmivity of bag}
b =  0.0002;     {Membrane thickness}
sig = 0.8;        {Porosity of membrane}
ec = 0.94;        {Emmitivy}
Bi = 1.388E-3;    {Flowrate of water [kg/s]}
Cp = 4180;
Ac1p = 1.01;
Ac2p = 1.01;
Abag = 1.01;
Aw = 1.01;
Ac = 1.01;
Ma = 18;          {Molecular weight [kg/kmol]}
hfg = 2450000;    {Evaporation heat [J/kg] }
R = 8315;         {Gas constant [J/mol.K] }
rho = 1.16;       {Density [kg/m^3] }
cpa = 1007;       { J/kg.K }
Le = 0.769;       { Outside Lewis number }
Le2 = 0.9231;     {Inside Lewis number }
Fak = 1;          { J/Nm}
A1 = 23.238;      {Antionne constants }
B1 = 3841;
C1 = 45;
Acb = 1.01;
kw = 27E-3;       {W/m.K}
eb1 = 0.9;
hfg2 = 2440000;    {J/kg}
Pt = 101325;       {Atmospheric pressure [Pa]}
Abag1 = 1.01;
hfg3 = 2350000;
eb =  0.94;
hfg4 = 2366000;

var
f  :   text;
name : string[20];
GG : char;
Tbmin,Tbmax,Antwoord,Ts,verg4,hwp,Ant,Tcp1,Tcp2,Tcp1max,Tcp1mi
n,Th,
D1,hi,Tc,Tw,Ts1,T1max,T1min,T1,Tb,Tb2,Tw2,Tw1,Tbag,Tb1,D2,D3,V
erg5 : real;
Tb3,D4,Io,dp,xw,Ta,u,er,u2,hum : real;

procedure constants;
var
place : integer;
c: array[0..20] of real;
store : text;

function tester (message:string; value : real):real;
var
```

```
 code : integer;
 answr : real;
 input : string[20];

 begin
   write(message,' (',value:0:5,'):');
   readln(input);
     if input = '' then
     tester := value
   else
    begin
      val(input,answr,code);
      Tester := Answr;
    end;
   writeln;
 end;

 begin
   Assign (Store, 'a:cnstnts');
   reset(store);
     for place := 0 to 20 do
       readln(store,c[place]);
   close(store);
   clrscr;
   writeln('Double effect solar distiller input variables');
   writeln;
   c[0] := Tester ('Radiation(Io (W/m^2))',c[0]);
   c[1] := Tester (' Ambient Temperature(Ta(xK))',c[1]);
   c[2] := Tester ('Windspeed in front(u (m/s))',c[2]);
   c[3] := Tester (' Total reflection(er)',c[3]);
   c[4] := Tester ('Windspeed at back(u2(m/s)',c[4]);
   c[5] := Tester (' Relative humidity(hum)',c[5]);
   c[6] := Tester ('Front spacing(dp(m))',c[6]);
   c[7] := Tester (' Back spacing(xw(m))',c[7]);
   Assign(store,'a:cnstnts');
   Rewrite (store);
     for place := 0 to 20 do
       writeln(store,c[place]);
   close(store);
   assign(store,'a:cnstnts');
   reset(store);
   readln(store,Io);
   readln(store,Ta);
   readln(store,u);
   readln(store,er);
   readln(store,u2);
   readln(store,hum);
   readln(store,dp);
   readln(store,xw);
   close(store);
end;

procedure Tcover2;
var
  sum1,sum2,sum3,sum4,Tcp2max,Tcp2min : real;
 begin
    Tcp2max :=350;
    Tcp2min := 270;
```

```
        repeat
          Tcp2:= (Tcp2max + Tcp2min)/2;
           if Tcp1 < Tcp2 then
           Tcp2 := Tcp1 - 1
           else
           Tcp2 := Tcp2;
                  sum1 := Io*alcs +
ac1p*5.67E-8*ec1*(exp(4*ln(Tcp1))-exp(4*ln(Tcp2)));
                                sum2 :=
0.787/dp*exp(0.31*ln(dp*dp*dp*(Tcp1-Tcp2)))*(Tcp1-Tcp2)*Ac1p;
       sum3 := -Ac2p*(3.903*sqrt(u)*(Tcp2-Ta)+
                5.67E-8*(exp(4*ln(Tcp2))-exp(4*ln(Ts)))*ec2);
       sum4 := sum1 + sum2 +sum3;
         if sum4 > 0 then
           Tcp2min := Tcp2
         else
          if sum4 < 0 then
           Tcp2max := Tcp2
        until (sum4>-0.001) and (sum4 < 0.0001);
   end;

procedure Thot;

const
      Tref = 273.16;     {Reference temperature}
      Tinlet = 293.15;

var
   som1,som2,som3,Thmin,Thmax : real;
   begin
     Thmin :=270;
     Thmax :=1000;
       repeat
         Th := (Thmin + Thmax)/2;
              som1 := -Bi*cp*Tinlet/Ac2p +
Bi/Ac2p*cp*(2*Th-Tinlet)-Io*(1-er);
         som2 := Ac2p*(3.903*sqrt(u)*(Tcp2-Ta)+5.67E-8*ec2*
         (exp(4*ln(Tcp2))-exp(4*ln(Ts))));
         som3 := som1 + som2;
          if som3 <0 then
             Thmin := Th
           else
             if som3 > 0 then
                Thmax := Th;
       until (som3 < 0.0001) and (som3 > -0.0001);
    end;

procedure bag;

  const  alcs2 = 0.04;
       k = 650E-3;
       x = 0.07;
       Nu = 4.558;
       Pi = 3.1415;
  var
    Tbagmin,Tbmax : real;
  begin
    hwp := Nu*k/(4*0.1156*Pi*x/(2.3/5));
```

```
    Tbag := (Io*(1-(alcs+alcs2))+Th*hwp*Abag)/hwp/Abag;
  end;

procedure check;
  var
     verg1,verg2,verg3 : real;
  begin
    verg1 := hwp*(Th-Tcp1)*Abag+Io*(1-alcs)*alcs;
                      verg2                     :=
-Ac1p*(Tcp1-Tcp2)*0.787/dp*exp(0.31*ln(dp*dp*dp*(Tcp1-Tcp2)));
    verg3 := -Ac1p*5.67E-8*ec1*(exp(4*ln(Tcp1))-exp(4*ln(Tcp2)));
    verg4 := verg1 + verg2 + verg3;
  end;



procedure output1(name:string);
  begin
    WriteLn(f,'non-ideal situation');
    WriteLn(f,'Radiation',Io:0:4);
    WriteLn(f,'Amb.temp',Ta:0:4);
    WriteLn(f,'Windspeed',u:0:4);
    WriteLn(f,'Reflection',er:0:4);
    WriteLn(f,'Relative humid',hum:0:4);
    WriteLn;
    WriteLn(f,'dp =', dp:0:5);    {for sensitivity study}
    WriteLn(f,'xw =', xw:0:5);
  end;

procedure evap;  {Balance around T1}
  var
    sum5,Ts1min,Ts1max,sum1,sum2,sum3,sum4 : real;
  begin
  Ts1min := T1;
  Ts1max := 330;
   Repeat
    Ts1 := (Ts1min + Ts1max)/2;
    sum1 := -3.908*sqrt(u2)*(Ta-T1)*Acb-5.67E-8*ecb*Acb*
         (exp(4*ln(Ts))-exp(4*ln(T1)));
                        sum2                    :=
-0.613/de*(0.292+132*exp(0.327*ln(de*de*de*(Ts1-T1))))*(Ts1-T1);
                        sum3                    :=
Ma*hfg*3.908*sqrt(u2)*fak/(R*rho*cpa*(exp(2/3*ln(Le))))
         *(exp(A1-B1/(T1-C1))/T1-Hum*exp(A1-B1/(Ta-C1))/Ta);
    sum4 := sum1 + sum2 + sum3;
      if sum4 < 0 then
          Ts1max := Ts1
           else
      if sum4 > 0 then
          Ts1min := Ts1;
   until (sum4 > -0.00001) and (sum4 < 0.00001);
  end;

procedure evap2;  {Balance around Ts1}
 var
   Tb1min,Tb1max,sum1,sum2,sum3,sum4 : real;
   begin
     Tb1min := 290;
```

```
     Tb1max := 400;
       repeat
        Tb1 := (Tb1min + Tb1max)/2;
                                    sum1                         :=
-kw/xw*(Tb1-Ts1)*Aw-Abag1*5.67E-8*(exp(4*ln(Tb1))-exp(4*ln(Ts1
)))*eb1;
                                                                sum2
:=0.613/de*(0.292+132*exp(0.327*ln(de*de*de*(Ts1-T1))))*(Ts1-T1);
                                    sum3                         :=
-1.138E-6*hfg2*1/(b/(sig*sqrt(Tb1))+xw/sqrt(Ts1))*ln
        ((1-exp(A1-B1/(Ts1-C1))/Pt)/(1-exp(A1-B1/(Tb1-C1))/Pt));
        sum4 := sum1 + sum2 +sum3;
        if sum4 > 0 then
          Tb1min := Tb1
          else
        if sum4 < 0 then
          Tb1max := Tb1;
      until (sum4 <0.0001) and (sum4 > -0.0001);
   end;

procedure Evap3;  {Balance around Tb1}
  var
    Twmin,Twmax,sum1,sum2,sum3,sum4 : real;
  begin
    Twmin := Tb1;
    Twmax :=400;
       repeat
      Tw := (Twmin + Twmax)/2;
                               sum1                              :=
Aw*kw/xw*(Tb1-Ts1)+Abag1*eb1*5.67E-8*(exp(4*ln(Tb1))-
         exp(4*ln(Ts1)));
      D4 := 1.138E-6*hfg3*1/(b/(sig*sqrt(Tb1))+xw/sqrt(Ts1))*ln

((1-exp(A1-B1/(Ts1-C1))/Pt)/(1-exp(A1-B1/(Tb1-C1))/Pt));
      sum3 := -hwp*(Tw-Tb1)*Aw;
      sum4 := sum1 + D4 + sum3;
       if sum4 > 0 then
         Twmin := Tw
          else
        if sum4 < 0 then
           Twmax := Tw
      until (sum4 < 0.0001) and (sum4 > -0.0001);
   end;

procedure extra; {Balance to calculate Tw}
  var
    sum1,Tbmin,Tbmax : real;
   begin
        Tbmin := Tw;
        Tbmax := 370;
     repeat
       Tb := (Tbmin + Tbmax)/2;
       sum1 := Aw*hwp*(Tb-Tw)-Aw*hwp*(Tw-Tb1);
       if sum1 < 0 then
        Tbmin := Tb
          else
       if sum1 > 0 then
        Tbmax := Tb;
```

```
     until (sum1 <0.0001) and (sum1 > -0.0001);
   end;

procedure dubbel;
  var
    Tb2max,Tb2min,sum1,sum2,sum3,sum4 : real;
  begin
    Tb2min := 290;
    Tb2max := 400;
     repeat
       Tb2 := (Tbmin + Tbmax)/2;
                                sum1 :=
-kw/xw*(Tb2-Tb)*Aw-Abag1*5.67E-8*(exp(4*ln(Tb2))-exp(4*ln(Tb))
)*eb1;
       sum2 := Aw*hwp*(Tb-Tw);
       sum3 :=-1.138E-6*hfg2*1/(b/(sig*sqrt(Tb2))+xw/sqrt(Tb))*

ln((1-exp(A1-B1/(Tb-C1))/Pt)/(1-exp(A1-B1/(Tb2-C1))/Pt));
       sum4 := sum1 + sum2 + sum3;
        if sum4 > 0 then
         Tb2max := Tb2
           else
        if sum4 < 0 then
          Tb2max := Tb2;
     until ( sum4 < 0.0001) and (sum4 > -0.0001);
  end;


procedure dubbel2;  {Balance aroundTb2}
  var
    Tw1max,Tw1min,sum1,sum2,sum3,sum4 : real;
  begin
    Tw1min := Tb2;
    Tw1max := 400;
     repeat
       Tb1 := (Tw1min + Tw1max)/2;
                                sum1 :=
Aw*kw/xw*(Tb2-Tb)-Abag1*eb1*5.67E-8*(exp(4*ln(Tb2))-exp(4*ln(T
b)));
       sum2 := Aw*hwp*(Tb-Tw);
       sum3 := 1.138E-6*hfg3*1/(b/(sig*sqrt(Tb2))+xw/sqrt(Tb))*

ln((1-exp(A1-B1/(Tb-C1))/Pt)/(1-exp(A1-B1/(Tb2-C1))/Pt));
       sum4 := sum1 + sum2 + sum3;
        if sum4 > 0 then
         Tw1min := Tw1
           else
        if sum4 < 0 then
          Tw1max := Tw1;
     until ( sum4 < 0.0001) and (sum4 > -0.0001);
  end;

procedure dubbel3;  {Balance around Tw1}
  var
    Tb3max,Tb3min,sum1 : real;
  begin
    Tb3min := Tw1;
    Tb3max := 380;
```

```
     repeat
       Tb3 := (Tb3min + Tb3max)/2;
       sum1 := Aw*hwp*(Tb3-Tw1) - Aw*hwp*(Tw1-Tb2);
       if sum1 < 0 then
         Tb3min := Tb3
           else
        if sum1 > 0 then
          Tb3max := Tb3;
     until ( sum1 < 0.0001) and (sum1 > -0.0001);
  end;

procedure check1;
var
  Tcmin,Tcmax,sum1,sum2,sum3 : real;
  begin
    Tcmin := 290;
    Tcmax := Tb3;
   repeat
    Tc := (Tcmin + Tcmax)/2;
    hi := 0.787/dp*exp(0.31*ln(dp*dp*dp*(Tb3-Tc)));
                            D      1                   :      =
Ma*hi/(R*rho*cpa*exp(2/3*ln(Le2)))*(exp(A1-B1/(Tb3-C1))/Tb3-
    exp(A1-B1/(Tc-C1))/Tc);
    sum1 := hi*(Tb3-Tc)+Io*alcs+Aw*eb*5.67E-8*
            (exp(4*ln(Tb3))-exp(4*(Tc)));
   sum2 :=-Ac*(3.908*sqrt(u)*(Tc-Ta)+5.67E-8*ec*(exp(4*ln(Tc))-
   exp(4*ln(Ts))));
   antwoord := sum1 + sum2;
     if antwoord < 0 then
         Tcmax := Tc;
    until (antwoord > -0.0001) and (antwoord <0.0001);
  end;

procedure check2;
var
   Verg1,verg2,verg3 : real;
    begin
     D2 :=  1.138E-6*1/(b/(sig*sqrt(Tb2))+xw/sqrt(Tb))*

ln((1-exp(A1-B1/(Tb-C1))/Pt)/(1-exp(A1-B1/(Tb2-C1))/Pt));
     D4 := D4/hfg3;
     Verg1 := -Io*(1-er)+(D2)/Ac*Cp*((Tc+Tb)/2)+D4/Abag1*Cp*Ts1
               -Bi*Cp/Ac*Th+(Bi-D2-D4)/Ac*Cp*Th;
                        V    e    r    g    2            :      =
Ac*(3.908*sqrt(u)*(Tc-Ta)+5.67E-8*ec*(exp(4*ln(Tc))-

exp(4*ln(Ts))))-5.67E-8*Acb*ecb*(exp(4*ln(Ts))-exp(4*ln(T1)));
                        V    e    r    g    3            :      =
Ma*hfg*3.908*sqrt(u2)/(R*rho*cpa*(exp(2/3*ln(Le))))*
              (exp(A1-B1/(T1-C1))/T1-hum*exp(A1-B1/(Ta-C1))/Ta)*
              -3.908*sqrt(u2)*(Ta-T1)*Acb;
     Verg5 := Verg1 + Verg2 + Verg3;
    end;

procedure output2(name:string);
begin
     WriteLn(f);
     WriteLn(f,'    Membrane bag calculations');
```

```
     WriteLn(f);
     WriteLn(f,'     T1 = ',T1:7:3,' K');
     WriteLn(f,'     Ts1 = ',Ts1:7:3,' K');
     WriteLn(f,'     Tb1 = ',Tb1:7:3,' K');
     WriteLn(f,'     Tw = ',Tw:7:3,' K');
     WriteLn(f,'     Tb = ',Tb:7:3,' K');
     WriteLn(f,'     Tb2 = ',Tb2:7:3,' K');
     WriteLn(f,'     Tw1 = ',Tw1:7:3,' K');
     WriteLn(f,'     Tb3 = ',Tb3:7:3,' K');
     WriteLn(f,'     Tc = ',Tc:7:3,' K');
     WriteLn(f);
     WriteLn(f,'Prod at back = ',D2:0:5,' kg/hr.m^2');
     WriteLn(f,'Prod at back of second bag = ',D4:0:5,'
kg/hr.m^2');
     WriteLn(f,'Total production = ',D3:0:5,' kg/hr.m^2');
end;

procedure choice;
var
dev : char;
device : string[4];

 begin
   WriteLn(' Please select option ');
   WriteLn;
   WriteLn(' Printer or screen (P/S)');
   Dev := Readkey;
   if upcase(dev) = 'S' then
   name := 'con'
    else
    name := 'lpt1';
  end;

  begin
   constants;
   ClrScr;
   Tcp1min := 310;
   Tcp1max := 393;
   Ts :=Ta - 6;
     repeat
      WriteLn('       Wait    ');
       Tcp1 := (Tcp1max + Tcp1min)/2;
       Tcover2;
       Thot;
       Bag;
       check;
        if verg4 < 0 then
          Tcp1max := Tcp1
           else
             Tcp1min := Tcp1;
             ClrScr;
     until (verg4 < 0.0001) and (verg4 > -0.0001);
       choice;
       ClrScr;
       Assign(f,name);
       Rewrite(f);
       output1 (name);
       T1min := 290;
```

```
      T1max := 320;
    repeat
      T1 := (T1min + T1max)/2;
      evap;
      evap2;
      evap3;
      extra;
      dubbel;
      dubbel2;
      dubbel3;
      check1;
      check2;
     if verg5 < 0 then
       T1min := T1
     else
     if verg5 > 0 then
       T1max := T1;
    until (verg5 <0.0001) and (verg5 > -0.0001);
      D3 := (D2 + D4)/3600;
      D2 := D2*3600;
      D4 := D4/3600;
      output2(name);
      close(f);
      GG := ReadKey;
 end.
```

2.1 PREHEATER RESULTS

Table 1 : Variable input is solar radiation.

RADIATION	OUTSIDE COVER	INSIDE COVER	BAG
500	306.620	319.449	327.366
520	307.125	320.434	328.677
550	307.885	321.906	330.639
560	308.139	322.395	331.292
580	308.648	323.372	332.596
600	309.157	324.346	333.897
630	309.922	325.801	335.845
640	310.178	326.285	336.494
670	310.946	327.734	338.435
680	311.202	328.215	339.081
700	311.715	329.176	340.371
730	312.486	330.612	342.303
740	312.743	331.090	342.946
760	313.259	332.043	344.230

Table 2 : Variable input is ambient temperature.

AMBIENT TEMP.	OUTSIDE COVER	INSIDE COVER	BAG
290	306.517	326.772	338.307
293	308.457	327.664	339.073
295	309.756	328.265	339.589
298	311.715	329.176	340.371
300	313.027	329.789	340.898
303	315.006	330.719	341.679
307	317.662	331.977	342.777

Table 3 : Variable input is windspeed.

WINDSPEED	OUTSIDE COVER	INSIDE COVER	BAG
1.00	313.196	329.868	340.966
1.60	312.216	329.409	340.572
1.90	311.832	329.230	340.418
2.00	311.715	329.176	340.371
2.10	311.603	329.124	340.326
2.50	311.195	328.933	340.163
2.80	310.923	328.807	340.055
3.20	310.598	328.656	339.925
3.90	310.107	328.428	339.729
5.00	309.477	328.136	339.478
9.00	307.956	327.433	338.875

Table 4 : Variable input is total reflection.

REFLECTION	OUTSIDE COVER	INSIDE COVER	BAG
0.10	311.715	329.176	340.371
0.13	311.151	328.038	339.136
0.18	310.215	326.133	337.070
0.25	308.911	323.449	334.163
0.40	306.148	317.625	327.870
0.50	304.334	313.683	323.625

2.2 MEMBRANE BAG RESULTS

2.2.1 SINGLE-EFFECT UNIT

Table 5 : Variable input is solar radiation.

RADIATION	Tc	Tb	Tw	Tb1	Ts1	T1	PROD1	PROD2	TOTAL
500	306.71	313.51	309.00	304.47	302.00	299.35	0.359	0.088	0.447
520	307.31	314.32	309.64	304.96	302.45	299.73	0.374	0.095	0.469
550	308.22	315.52	310.60	305.68	303.12	300.29	0.397	0.105	0.501
560	308.52	315.92	310.92	305.92	303.34	300.48	0.404	0.108	0.512
580	309.13	316.70	311.55	306.39	303.77	300.84	0.420	0.115	0.534
600	309.74	317.48	312.17	306.85	304.20	301.20	0.435	0.122	0.557
630	310.65	318.64	313.09	307.53	304.84	301.74	0.458	0.132	0.591
640	310.96	319.03	313.39	307.75	305.04	301.91	0.466	0.136	0.602
670	311.88	320.17	314.29	308.42	305.67	302.43	0.489	0.147	0.636
680	312.18	320.54	314.56	308.63	305.87	302.61	0.497	0.151	0.648
700	312.80	321.29	315.18	309.07	306.28	302.95	0.513	0.159	0.671
730	313.72	322.41	316.05	309.70	306.14	303.45	0.536	0.170	0.707
740	314.03	322.78	316.34	309.91	307.08	303.62	0.544	0.174	0.718
760	314.64	323.51	316.92	310.33	307.48	303.95	0.560	0.182	0.742

Table 6 : Variable input is ambient temperature.

TEMP.	Tc	Tb	Tw	Tb1	Ts1	T1	PROD1	PROD2	TOTAL
290	307.06	317.27	311.37	305.46	302.32	299.08	0.473	0.165	0.638
293	309.22	318.77	312.79	306.81	303.81	300.53	0.488	0.163	0.651
295	310.65	319.77	313.74	307.71	304.80	301.50	0.498	0.162	0.659
298	312.80	321.29	315.18	309.07	306.28	302.95	0.513	0.159	0.671
300	314022	322.31	316.31	309.97	307.27	303.91	0.523	0.156	0.679
303	316.35	323.86	317.60	311.34	308.76	305.36	0.538	0.153	0.691
307	319.19	325.94	319.56	313.17	310.75	307.30	0.559	0.146	0.705

Table 7 : Variable input is windspeed.

WINDSPEED	Tc	Tb	Tw	Tb1	Ts1	T1	PROD1	PROD2	TOTAL
1.00	315.92	324.19	318.23	312.27	309.92	306.65	0.518	0.173	0.691
1.60	313.78	322.21	316.14	310.07	307.43	304.12	0.515	0.163	0.678
1.90	313.02	321.50	315.40	309.29	306.54	303.21	0.513	0.160	0.673
2.00	312.80	321.29	315.18	309.07	306.28	302.95	0.513	0.159	0.671
2.10	312.59	321.10	314.97	308.85	306.03	302.69	0.512	0.158	0.670
2.50	311.83	320.40	314.24	308.09	305.16	301.80	0.510	0.158	0.668
2.80	311.35	320.00	313.78	307.60	304.59	301.23	0.509	0.152	0.661
3.20	310.80	319.45	313.24	307.04	303.94	300.57	0.507	0.150	0.657
3.90	310.00	318.71	312.47	306.23	303.00	299.62	0.505	0.147	0.651
5.00	309.02	317.81	311.53	305.25	301.86	298.46	0.501	0.143	0.644
9.00	306.90	315.86	309.49	303.13	299.35	295.92	0.492	0.134	0.626

Table 8 : Variable input is total reflection.

REFLECTION	Tc	Tb	Tw	Tb1	Ts1	T1	PROD1	PROD2	TOTAL
0.100	312.80	321.29	315.18	309.07	306.28	302.95	0.513	0.159	0.671
0.130	312.10	320.40	314.48	308.55	305.80	302.54	0.494	0.149	0.643
0.180	310.93	319.00	313.29	307.68	304.98	301.86	0.463	0.133	0.597
0.250	309.32	316.75	311.58	306.42	303.80	300.86	0.420	0.113	0.533
0.400	305.90	311.95	307.74	303.52	311.95	305.90	0.331	0.072	0.403
0.500	303.66	308.58	305.01	301.43	299.23	297.02	0.272	0.048	0.321

Table 9 : Variable input is relative humidity.

REL.HUM.	Tc	Tb	Tw	Tb1	Ts1	T1	PROD1	PROD2	TOTAL
10.00	312.41	320.79	314.61	308.42	305.52	302.16	0.515	0.153	0.668
15.00	312.60	321.04	314.90	308.75	305.90	302.55	0.514	0.156	0.670
20.00	312.80	321.29	315.18	309.07	306.28	302.95	0.513	0.159	0.671
25.00	312.99	321.54	315.46	309.38	306.65	303.34	0.512	0.161	0.673
30.00	313.19	321.78	315.74	309.70	307.02	303.72	0.510	0.164	0.675
50.00	313.95	322.73	316.83	310.93	308.46	305.21	0.505	0.175	0.680

Table 10 : Variable input is spacing : front spacing 0.04 m.

BACK SPACING	PRODUCTION 1	PRODUCTION 2	TOTAL
0.001	0.513	0.159	0.671
0.002	0.495	0.172	0.667
0.003	0.475	0.183	0.658
0.004	0.455	0.194	0.649

Table 11 : Variable input is spacing : front spacing 0.05 m.

BACK SPACING	PRODUCTION 1	PRODUCTION 2	TOTAL
0.001	0.513	0.159	0.671
0.002	0.495	0.172	0.667
0.003	0.475	0.183	0.658
0.004	0.455	0.194	0.649

Table 12 : Variable input is spacing : front spacing 0.07 m.

BACK SPACING	PRODUCTION 1	PRODUCTION 2	TOTAL
0.001	0.513	0.159	0.671
0.004	0.455	0.194	0.649

2.2.2 DOUBLE-EFFECT UNIT

Table 13 : Variable input is solar radiartion.

RADIATION	Tc	Tb3	Tw1	Tb2	Tb	Tw	Tb1	Ts1	T1
500	310.94	319.21	315.45	311.68	310.19	306.31	302.43	300.14	297.78
520	311.71	320.17	316.28	312.39	310.89	306.88	302.87	300.53	298.12
550	312.87	321.60	317.52	313.43	311.93	307.72	303.51	301.12	298.61
560	313.26	322.07	317.92	313.78	312.27	307.99	303.72	301.31	298.77
580	314.04	323.01	318.73	314.46	312.95	308.54	304.13	301.69	299.09
600	314.82	323.94	319.54	315.13	313.63	309.08	304.54	302.06	299.41
630	316.00	325.32	320.72	316.13	314.63	309.89	305.15	302.62	299.88
640	316.39	325.77	321.12	316.46	314.96	310.15	305.34	302.80	300.03
670	317.57	327.13	322.28	317.44	315.94	310.94	305.93	303.35	300.49
680	317.96	327.58	322.67	317.76	316.26	311.19	306.13	303.53	300.64
700	318.75	328.47	323.44	318.40	316.91	311.71	306.51	303.88	300.94
730	319.93	329.80	324.58	319.35	317.87	312.47	307.07	304.41	301.38
740	320.32	330.24	324.95	319.67	318.18	312.72	307.26	304.59	301.53
760	321.11	331.11	325.70	320.29	318.81	313.22	307.83	304.93	301.82

RADIATION	PRODUCTION 1	PRODUCTION 2	PRODUCTION 3	TOTAL
500	0.326	0.141	0.300	0.767
520	0.340	0.151	0.312	0.802
550	0.360	0.166	0.330	0.856
560	0.367	0.171	0.336	0.874
580	0.380	0.181	0.349	0.910
600	0.394	0.191	0.361	0.946
630	0.414	0.208	0.380	1.001
640	0.421	0.213	0.386	1.020
670	0.441	0.230	0.405	1.075
680	0.448	0.235	0.411	1.094
700	0.462	0.247	0.424	1.132
730	0.482	0.264	0.442	1.188
740	0.489	0.270	0.449	1.208
760	0.503	0.282	0.462	1.246

Table 14 : Variable input is temperature.

TEMP.	Tc	Tb3	Tw1	Tb2	Tb	Tw	Tb1	Ts1	T1
290	312.94	324.32	319.44	314.56	312.84	307.80	302.76	299.79	296.91
293	315.13	325.86	320.92	315.99	314.36	309.26	304.17	301.33	298.43
295	316.58	326.90	321.92	316.95	315.37	310.24	305.10	302.35	299.43
298	318.75	328.47	323.44	318.40	316.91	311.71	306.51	303.88	300.94
300	320.19	329.53	324.45	319.38	317.94	312.69	307.45	304.91	301.94
303	322.35	331.14	325.99	320.85	319.49	314.17	308.86	306.44	303.44
307	325.68	333.41	328.13	322.85	321.63	316.17	310.71	308.51	305.45

TEMPERATURE	PRODUCTION 1	PRODUCTION 2	PRODUCTION 3	TOTAL
290	0.434	0.249	0.389	1.072
293	0.444	0.248	0.402	1.094
295	0.451	0.248	0.411	1.109
298	0.462	0.247	0.424	1.132
300	0.469	0.245	0.432	1.146
303	0.479	0.243	0.445	1.168
307	0.501	0.240	0.472	1.213

Table 15 : Variable input is windspeed.

WINDSPEED	Tc	Tb3	Tw1	Tb2	Tb	Tw	Tb1	Ts1	T1
1.00	321.98	331.13	326.17	321.21	319.92	314.79	309.66	307.41	304.49
1.60	319.79	329.32	324.31	319.29	317.86	312.68	307.50	305.00	302.06
1.90	318.99	328.67	323.64	318.60	317.13	311.93	306.73	304.14	301.19
2.00	318.75	328.47	323.44	318.40	316.91	311.71	306.51	303.88	300.94
2.10	318.52	328.29	323.25	318.21	316.70	311.50	306.29	303.64	300.70
2.50	317.70	327.63	322.58	317.53	315.97	310.78	305.54	302.80	299.84
2.80	317.17	327.21	322.15	317.10	315.50	310.28	305.06	302.25	299.30
3.20	316.55	326.72	321.66	316.59	314.96	309.73	304.51	301.63	298.67
3.90	315.64	326.00	320.93	315.86	314.17	308.94	303.70	300.72	297.76
5.00	314.51	325.13	320.05	314.97	313.21	307.98	302.74	299.63	296.67
9.00	311.92	323.18	318.10	313.03	311.11	305.87	300.64	297.24	374.29

WINDSPEED	PRODUCTION 1	PRODUCTION 2	PRODUCTION 3	TOTAL
1.00	0.464	0.255	0.434	1.153
1.60	0.463	0.249	0.427	1.139
1.90	0.462	0.247	0.424	1.133
2.00	0.462	0.247	0.424	1.132
2.10	0.461	0.246	0.423	1.130
2.50	0.460	0.244	0.419	1.1240
2.80	0.459	0.243	0.417	1.119
3.20	0.458	0.242	0.414	1.114
3.90	0.456	0.240	0.410	1.106
5.00	0.453	0.238	0.404	1.095
9.00	0.445	0.235	0.390	1.070

Table 16 : Variable input is total reflection.

REFLECTION	Tc	Tb3	Tw1	Tb2	Tb	Tw	Tb1	Ts1	T1
0.100	318.75	328.47	323.44	318.40	316.91	311.71	306.51	303.88	300.94
0.130	317.84	327.41	322.53	317.64	316.14	311.10	306.05	303.46	300.58
0.180	316.33	325.62	320.99	316.35	314.85	310.06	305.28	302.75	299.11
0.250	314.22	323.07	318.79	314.51	313.00	308.58	304.16	301.71	299.15
0.400	309.78	317.38	313.86	310.34	308.86	305.23	301.60	299.39	297.15
0.500	306.88	313.37	310.37	307.36	305.93	302.84	299.75	297.73	295.75

REFLECTION	PRODUCTION 1	PRODUCTION 2	PRODUCTION 3	TOTAL
0.100	0.462	0.247	0.424	1.132
0.130	0.445	0.232	0.409	1.086
0.180	0.419	0.210	0.384	1.012
0.250	0.381	0.179	0.350	0.909
0.400	0.301	0.119	0.277	0.697
0.500	0.249	0.083	0.230	0.562

Table 17 : Variable input is relative humidity.

REL.HUM.	Tc	Tb3	Tw1	Tb2	Tb	Tw	Tb1	Ts1	T1
10.00	318.42	328.10	322.99	317.89	316.34	311.07	305.80	303.06	300.08
15.00	318.58	328.28	323.22	318.15	316.63	311.39	306.16	303.16	300.51
20.00	318.75	328.47	323.44	318.40	316.91	311.71	306.51	303.88	300.94
25.00	318.91	328.66	323.85	318.65	317.19	312.02	306.86	304.29	301.36
30.00	319.06	328.84	323.87	318.90	317.46	312.33	307.20	304.69	301.77
50.00	319.69	329.56	324.72	319.88	318.54	313.54	308.54	306.54	303.38

RELATIVE HUMIDITY	PRODUCTION 1	PRODUCTION 2	PRODUCTION 3	TOTAL
10.00	0.466	0.241	0.425	1.132
15.00	0.464	0.244	0.424	1.132
20.00	0.462	0.247	0.424	1.132
25.00	0.459	0.249	0.423	1.131
30.00	0.457	0.252	0.422	1.131
50.00	0.448	0.261	0.418	1.128

Table 18 : Variable input is spacing : front spacing 0.04 m.

BACK SPACING	PROD. 1	PROD. 2	PROD. 3	TOTAL
0.001	0.462	0.247	0.42353	1.132
0.002	0.442	0.264	0.40212	1.108
0.003	0.422	0.279	0.37898	1.080
0.004	0.404	0.292	0.35777	1.054

Table 19 : Variable input is spacing : front spacing 0.05 m.

BACK SPACING	PROD. 1	PROD. 2	PROD. 3	TOTAL
0.001	0.462	0.247	0.42353	1.132
0.002	0.442	0.264	0.40212	1.108
0.003	0.422	0.279	0.37898	1.080
0.004	0.404	0.292	0.35777	1.054

Table 20 : Variable input is spacing : front spacing 0.07 m.

BACK SPACING	PROD. 1	PROD. 2	PROD. 3	TOTAL
0.001	0.462	0.247	0.42353	1.132
0.004	0.404	0.292	0.35777	1.054

2.3 DIMENSIONS

Temperature	K
Ambient temperature	K
Radiation (Io)	W/m2
Windspeed	m/s
Production	kg/(h.m2)
Relative humidity	%
Back spacing	m

SOLAR DISTILLATION UNIT

D.W. SCHOEMAN

The combination of excess quantities of both solar energy and non-potable water in South Africa, gave rise to the idea to attempt to desalinate this water on an economical scale.

With the lack of electricity and other resources in remote regions, the advantage of being able to use a solar distillation unit lies in the fact that solar energy is the only source of energy required.

Taking the market into account, the properties of the unit must include the following:

1. Easy of handling (portable)
2. Low maintenance costs
3. Strength (robustness)
4. Simplicity of operation.

Concentration of feed solution: 1650 - 2100 ppm NaCl
Concentration of permeate: 215 - 400 ppm NaCl
Percentage retention: 85 - 90 %

FUTURE DEVELOPEMENTS

The concept of evaporation through a microporous membrane using solar energy has been demonstrated. Several aspects of the project require further developement; these include:

1. Adequate sealing techniques
2. More effective forced circulation to maximize vaporization
3. Enhanced removal of condensate
4. Easier to operate in and outlets
5. The use of multiple stages.

Production rates of membranes A and B at different heated water temperatures are given in **Table 1**:

	MEMBRANE A	**MEMBRANE B**
Heated water temperature [°C]	Production rate [$^{l}/m^{2}.h$]	Production rate [$^{l}/m^{2}.h$]
48		0.517
50	0.074	
53		0.553
54	0.078	
57		0.587
60	0.161	
61		0.652
62	0.184	
65	0.193	0.736
76	0.330	

TABLE 1

RESULTS

The results produced by the aluminium plate and frame model proved that the model can be used to produce potable water by using solar energy.

Transition from the plate and frame model to a portable, easy to operate model that does not require any electric pumps, is, however, not too easy, especially since the protection of the membrane must be kept as a priority.

With the temperature of the condensing surface at a constant 14°C, two types of membranes were tested, one with a protection cloth on both sides of the membrane (A), and the other with a cloth on only the one side of the membrane (B).

MATERIALS AND CONSTRUCTION

Initially canvass bags were used. Later an aluminium plate and frame model was used, to determine the feasability of the idea. The water was heated to certain temperatures and then placed between the plate and the membrane. Forced flow patterns were established to ensure constant circulation, and thus constant vaporization. Cooling water was circulated at the back of another plate to condense the vapour. The condensate was then collected through a outlet.

PRINCIPLE

Solar energy can be used to heat contaminated water to produce a vapour which is free from any contamination. In order to seperate this vapour from the contaminated water, it is necessary to use a membrane which only allows the vapour through, leaving the contaminated water behind. To obtain potable water, the vapour must be condensed on a surface which is cooler than the heated water. The principal is illustrated in **Figure 1**.

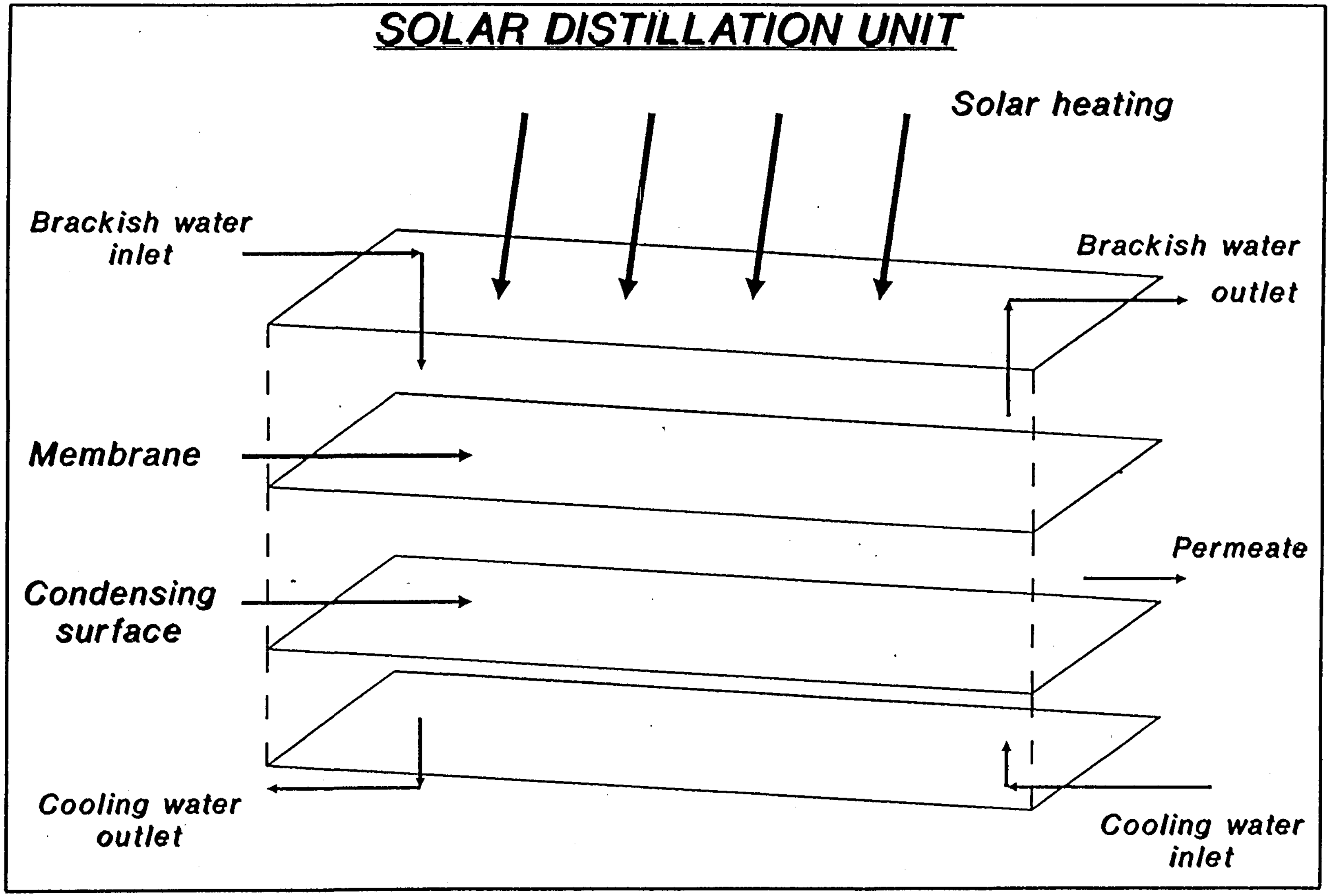
SOLAR DISTILLATION UNIT
Solar heating
Brackish water inlet
Brackish water outlet
Membrane
Permeate
Condensing surface
Cooling water outlet
Cooling water inlet

FIGURE 1

When the vapour condenses, heat is generated, and this heat can be used efficiently to heat another stage of distillation. With this re-use of energy, the production rate can be increased above that of a single stage distillation unit.

Factors which are most likely to influence the production rate are:

1. Amount of solar heat
2. Temperature of the water which is fed to the system
3. Windspeed, the reflection and absorbtion of sunlight
4. Thickness of spacer material between the membrane and the condensing surface.

An initial model, in the form of a computer program was developed with the aim of testing such a model against the experimental results.