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A PROJECT TO DEVELOP A LABORATORY FOR TESTING SOLAR COLLECTORS FOR THERMAL HEATING SYSTEMS IN KENYA

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NOMENCLATURE

a,b = constants used in incident angle modifier equation, dimensionless

A = cross-sectional area, m^2 (ft^2)

A_a = transparent frontal area for a flat-plat collector or aperture area for a concentrating collector, m^2 (ft^2)

A_g = gross collector area, m^2 (ft^2)

A_n = area of nozzle, m^2 (ft^2)

A_r = absorbing area of a flat-plate collector or the receiving area of a concentraring collector, m^2 (ft^2)

b_o = constant used in incident angle modifier equation, dimensionless

C_A = effective heat capacity of the solar collector, J/°C(Btu/F)

c_p = specific heat of the transfer fluid, J/(kg·°C) (Btu/(lbm·F))

D_n = nozzle throat diameter, m(ft)

f_t = temperature factor for calculation of nozzle, Reynolds number, dimensionless

F' = absorber plate efficiency factor, dimensionless

F_R = solar collector heat removal factor, dimensionless

I = solar irradiation, W/m^2(Btu/(hr·ft^2))

I_D = direct solar irradiation component W/m^2(Btu/(hr.ft^2))

I_{DN} = direct normal solar irradiation, W/m^2(Btu/(hr·ft^2))

I_d = diffuse solar irradiation incident upon the aperture plane of collector, W/m^2(Btu/(hr·ft^2))

I_{sc} = solar constant, 1 353 W/m^2(429.2 Btu/(hr·ft^2))

I_t = total solar irradiation incident upon the aperture plane of collector, W/m^2(Btu/(hr·ft^2))

K = factor defined by equation (5.8), dimensionless

$K_{\alpha\tau}$ = incident angle modifier, dimensionless

m = air mass, dimensionless

$\dot{m}$ = mass flow rate of the transfer fluid, kg/s (lbm/hr)

N_{Re} = Reynolds number, dimensionless

P_{th} = theoretical power required to move the transfer fluid through the collector, W(hp)

P_n = absolute pressure at the nozzle throat, Pa(lbf/in.^{2})

P_v = velocity pressure at the nozzle throat or the static pressure difference across the nozzle, Pa(lbf/in.^{2})

Δp = pressure drop across the collector, Pa(lbf/in.^{2})

Δp_n = pressure drop across the nezzle, Pa(lbf/in.^{2})

Q_{mi} = measured air flow rate, $m^3/s(ft^3/min)$

Q_s = standard air flow rate, $m^3/s(ft^3/min)$

q_u = rate of useful energy extraction from the collector, W(Btu/hr)

t_a = ambient air temperature, °C(F)

t_f = average fluid temperature, °C(F)

$t_{f,e}$ = temperature of the transfer fluid leaving the collector, °C(F)

$t_{f,e,initial}$ = temperature of transfer fluid leaving the collector at the beginning of a specified time period, °C(F)

$t_{f,e,T}$ = temperature of the transfer fluid leaving the collector at a specified time, °C(F)

$t_{f,i}$ = temperature of the transfer fluid entering the collector. °C(F)

t_p = average temperature of the absorbing surface for a flat-plate collector, °C(F)

t_r = average temperature of the absorbing surface for a concentrating collector, °C(F)

Δt = temperature difference, °C(F)

U_L = solar collector heat transfer loss coefficient, $W/(m^2 \cdot °C)$ $(Btu/(hr \cdot ft^2 \cdot F))$

V_a = velocity of the air nozzle throat, m/s (ft/min)

v_n = specific volume of the air at the nazzle at standard barometric pressure, m^3/kg dry air (ft^3/lbm dry air)

v'_n = specific volume of air at the nozzle per unit mass of air-water vapor mixture, m^3/kg (ft^3/lbm)

w = density, kg/m^3 (lbm/ft^3)

W_n = humidity ratio at the nozzle, kg H_2O/kg dry air (lbm H_2O/lbm dry air)

α = absorptance of the collector absorber surface for solar radiation

Γ = fraction of specularly reflected radiation from the reflector or refracted radiation which is intercepted by the solar collector absorbing surface

γ = collector-solar azimuth, deg

θ = angle of incidence between direct solar rays and the normal to the collector surface or to the aperture, deg

β = solar altitude angle, deg

ϕ = solar azimuth angle, deg

ψ = collector azimuth angle, (measured from teh south in the horizontal plane), deg

η_g = collector efficiency based on gross collector area, %

λ = wavelength, μm

T = time, decimal hours or seconds

τ = transmittance of the solar collector cover plate, dimensionless (if no cover plate is used, τ=1.0)

$(\tau\alpha)_e$ = effective transmittance-absorptance product, dimensionless

$(\tau\alpha)_{e,n}$ = effective transmittance-absorptance product at normal incidence

T_1, T_2 = time at the beginning and end of a test period, decimal hours

Chapter I

Introduction

In Kenya, the development of the technology of Solar Water Heater Systems has taken shape where the approach takes the following six stages:

- Organizing the Solar Water Heating Industry through the formation of a consultative committee composed of representatives from manufacturers of the solar water heater systems, the house building industry, the Kenya Bureau of Standards, East Africa Power and Lighting Co., Ltd., architecturers, plumbers and the Ministry of Energy.
- The development of standards as guidelines.
- The development of testing laboratory for the systems.
- The development of data collection models for assessment and evaluation of the socioeconomic and performance aspects and also for statistical recording of rate of growth for the production of the systems.
- The development of a proposal for a mechanism of loans for both the manufacturers and the customers.
- Planning and organizing seminars and workshops.

The development of the first and second stages has been accomplished and now the task is to develop the third stage. The other remaining three stages can be developed simultaneously.

This project is therefore intended to develop a testing facility for flat-plate solar collectors. A Solar Collector is the major component in the solar thermal systems, which may include systems such as solar water heating, solar air heating and solar concentrators. Although the major purpose of the proposed testing facility is to test solar collectors for water heating, some consideration will be given to solar collectors for heating air since the applications of both of these do overlap sometimes.

Furthermore the application of solar collectors for crop drying is the next development in the solar thermal energy technology for Kenya in which case the heat transfer fluid will be air.

It must be noted that the testing procedures adopted here are those developed by the ASHRAE standards where changes have been made to suit conditions in Kenya. Since we are just at the starting point in the testing of these systems in Kenya, it is hoped that many more changes will come with experience.

Chapter II

2. Solar Collector Test Procedures:

2-1 First Inspection for Material and Design Considerations:

It is imperative that when a collector is received at the testing laboratory, inspection tests will be carried out and findings recorded for future reference. As a prerequisite, the testing personnel will require the manufacturer to provide a satisfactory manual for the collector and ensure that the collector structure and the material types used for the various collector components are acceptable in accordance to the material standards provided in the Kenya Standards/Guidelines for Solar Water Heater Systems.

2.1.1 Manual Criterion:

A manual shall be provided for each collector and shall contain the following information:

- Name, address and telephone number of the manufacturer
- Description of material type of all collector components and their durability.
- Description of installation procedures
- Description of operation procedures including operating pressure.
- Description of maintenance procedures
- Performance specification, which must meet the minimum standards established in the Kenya Standard Guidelines for the Solar Water Heater Systems.
- Describe hazards which might arise during operation or maintenance of the system. Also describe necessary precautions to be taken in order to avoid any hazards.

2.1.2 Collector Structures and Material Criteria:

The structure of the collector and its components must be able to withstand local-extreme environmental conditions.

- The frame mechanical structure and material must be able to withstand severe winds and storms, corrosive salts and extreme local temperatures.
- Glazing material must be transparent and non-reflective to solar radiation. It must have thermal characteristics good enough to withstand extreme local temperatures and be mechanically strong enough to withstand local severe winds and storms.
- Heat transfer fluid in Kenya is usually water, but when other fluids are used, any such fluids shall not give rise to excessive precipitation or otherwise lose their homogeneity, boil, change absorptivity, or change pH or viscosity beyond the design range when exposed to their extreme operating temperatures and pressures during their design lifetime.
- Fluid passage material and design, shall have good heat conduction characterisitics, corrosion free, and designed and constructed in such a way as to allow optimum heat collection by spacing the riser pipes as closely as possible and with complete contact to the absorber.

- Bottom cover - shall be of durable material that will not corrode the frame at the joints where the two materials contact.
- Insulation - shall include the glazing which must have an air tight space between itself and the absorbing surface. Acceptable insulation material shall be put between the underneath of the absorber and the bottom cover. This material shall be able to maintain its insulative characteristics at the extreme operating temperatures during the life of the collector.
- Absorber - the material and coating layer of the absorber shall possess heat conductive, absorptive and non-reflective characteristics for solar radiation waves.
- The coating layer shall withstand extreme operating temperatures without pulling off.

2.2 First Pressure Test

The second test for the collector will be for the pressure to ensure that it will handle both the ordinary pipe water pressure and the hot water tank pressure as will be described in the collector manual and also in the Kenya Standard Guidelines for Solar Heater Systems.

It is necessary to note that the usual collectors in Kenya fall under the natural thermal convection mode and therefore, the chance of having collectors subjected to ordinary pipe water pressure is very slim.

However, if any collector is intended to have direct contact with ordinary pipe water pressure, their design shall be able to withstand the test pressure of 1,100 kPa gauge (160 psig). This test requirement shall be based on the assumption that the test pressure is twice the allowable water pipe pressure (550 kPa gauge 80 psig) in dwelling places. The pressure expected from hot tanks is in the region of 1030 kPa (150 psig) where a relief valve, at this pressure, shall be installed in the hot water storage tank.

The pressure test for the separated Solar Water Heater System which is separated from the ordinary pipe water pressure (mainly natural convection mode) shall be 1.5 times the manufacturers rated operating gauge pressure, but with a minimum of 170 kPa gauge (25 psig). Collectors specified for operating pressure less than 550 kPa gauge (80 psig) shall be pressure tested at 1.5 times manufacturers rated operating gauge pressure or 1,100 kPa (psig 160), whichever is greater.

2.2.1 Pressure Test Procedures:

There are two recommended methods for testing pressure: one, using Hydrostatic pressure source for either air or liquid filled collectors and the other, using pneumatic pressure source-for only air filled collectors. Procedures for these tests are described here below:

1) Pressure Test for Liquid Heat Transfer Collectors

(a) A pressure gauge shall be attached to read pressure at the exit part of the collector, the collector completely filled with unheated fluid and the exit part clogged off.

(b) Hydraulic pressure shall be supplied via the inlet part until the gauge indicates the test pressure.

(c) After stable test pressure has been reached, the exit part shall be closed and the pressure monitored for 15 minutes.

2. Pressure Test for Air Transfer Collectors

(a) A pressure tap of pipe or tubing shall be sealed into the exit part of the test specimen and connected to a manometer which can be read directly to 2.5 Pa (0.01 inch water column) or to a pressure gauge of equivalent accuracy. An air volume meter accurate within 14.0 liters (±0.5 cubic feet) shall be placed in the air supply system between the supply source and the collector.

(b) Apply pressure via inlet port of 125 Pa (0.5 inch column) and monitor pressure for one hour. The volume of air added or removed in order to maintain the required pressure shall be documented.

2.3 Exposure Test

Exposure shall be conducted in two parts; one to verify the integrity of construction after at least 30 days of exposure to simulated operating conditions, and the other to verify the integrity of construction after thermal shock (water spray test), at different days during the 30 days of exposure.

2.3.1 Exposure Test Procedure:

(a) Liquid collectors shall be filled completely with clean liquid, following which the water shall be allowed to gravity-drain for 15 minutes with the collector mounted at a 15° tilt angle. The collector inlet and outlet shall be loosely sealed.

(b) Exposure conditions shall consist of 30 days of cumulative daily incident solar radiation flux of 17 MJ/m^2 day (1,500 Btu/ft^2 day) as measured in the plane of the collector aperture. The exposure conditions shall include at least one consecutive four-hour exposure period with a minimum instantaneous flux of 950 w/m^2 (300 Btu/ft^2 hr). The average baseline ambient temperature shall be 27°C (80°F) or higher during the four-hour exposure period.

(c) Data shall be recorded and reported during exposure testing and shall include integrated daily solar radiation data. A regular weekly scheduled visual inspection shall also be made, and a record of changes in the physical appearance of the collector shall be kept.

2.3.2 Thermal Shock-Water Spray Test:

The spray test shall be conducted for five minutes in three different days of the last 10 days of the 30 days of the Exposure test. It shall be conducted after at least one hour of direct sun at a minimum intensity of 850 w/m^2 (270 Btu/ft^2 hr.) and within two hours of solar noon.

The spray shall deliver water at a rate not less than 20 mL/S per square meter of collector (1.8 $gall/ft^2$ hr.) (2.9 inches of rainfall per hour) with the spray pattern designed to wet the surface that would be wet during a normal rain shower. Temperature of the water shall be 24°C $\pm$ 5°C (75 $\pm$ 10°F) during the spray test.

2.3.3 Thermal Shock-Cold Fill Test for Liquid Collector:

Cold fill shall be conducted once for at least five minutes during the last 10 days of the 30 day exposure test. The unfilled collector shall be exposed to full sun, not less than 950 w/m^2 (300 Btu/ft^2 hr.) for one hour. While the collector is so exposed, liquid shall be circulated through the collector for five minutes at a flow rate of approximately 17 mL/S per square meter of collector (1.5 gallons/hr. Ft^2). The temperature of the entering liquid shall be 24°C $\pm$ 5°C (75°F $\pm$ 10°F) during the test.

Solar collectors may be certified without the thermal shock/cold fill if their designs are such that cold refill of a hot collector is not allowed. This condition must be stated in the owner's manual by the manufacturer and shall be included in the certification document.

2.4 Second Pressure Test:

A second static pressure test following the provisions of the first pressure test, Section 2.2, shall be conducted after exposure and prior to thermal performance testing.

2.5 Collector Time-Constant Test:

The test for a time constant shall be conducted to determine the time required for the outlet fluid temperature to attain 63.2 percent of its steady state value following a step change in the input. This figure is used to determine the time period over which temperature and irradiance data are integrated to obtain the computed efficiency values for the thermal performance test. This test method shall conform to the standard procedures described in Chapter IV, "Procedures for Testing and Computations."

2.6 Thermal Performance Test:

Collectors which have passed the above tests, Sections 2.1 through 2.5, shall be allowed to undergo the Thermal Performance test. The purpose of this test is to determine instantaneous efficiency of the solar collector over a wide range of operating temperatures. Efficiency, η is determined as the ratio of collected energy, Q_u, to the total available energy, I_t, falling upon the entire collector area, A_c, thus:

$$\eta = \frac{Qu}{I_t A_c}$$

Collected energy (Q_u), is determined by the product of fluid mass flow ($\dot{m}$), specific heat (C_p), average collector area (A_c), temperature difference ($t_a - t_c$) - (ambient temperature minus average collector temperature) and time (T). Thus:

$$Q_u = \dot{m} \times C_p \times A_c \times (t_a - t_c)\ T. \quad (Btu/ft^2\ hr). \qquad (2.2)$$

Total collector energy is determined by accounting for the reflected energy, q_r, the absorbed energy, q_a, and the transmitted energy, q_t, thus:

$$I_t = q_r + q_a + q_t \qquad (2.3)$$

It is important to carry out the thermal collector tests for each collector for a total of 15 days in the following manner,

q_{clear}, for 5 clear days

q_{cloudy}, for 5 cloudy days or rainy days

$q_{semiclear}$, for 5 semiclear days.

The average collected energy, $\overline{Q}_u$, for the total days shall give the real collector energy, Q_u, ($\overline{Q}_u = Q_u$).

For unglazed collectors, the inlet fluid temperatures include test temperatures below and above ambient air temperature. Glazed collectors are normally tested over a range of inlet fluid temperatures from near ambient to approximately 70°C (126°F) above ambient temperature.

The Method of testing shall conform to the test procedures in Chapter IV, Test Procedures and Computations.

2.7 Collector Incident Angle Modifier:

To predict the performance of a collector, for a wide range of conditions, tests shall be conducted to determine the collector incident angle modifier, $K_{\tau\alpha}$, which must be found for the computation of the collector performance. This is used to modify the efficiency curve (determined within 30 degrees of normal incidence) to account for changes in performance as a function of the sun's incident angle, θ. The test method used shall conform to the Test procedures in Chapter IV, Section 4.2.3.

2.8 Last Inspection for Material and Design Considerations:

The collector which has undergone all tests, sections 2.1 through 2.7, shall be dissembled and all visible defects identified, as per Kenya Standard Guidelines for Solar Water Heater Systems.

Chapter III

3. Instrument Specifications:

3.1 Solar Radiation Measurement:

The measurement of the two types of Radiation are possible and can be measured using two different instruments. A pyranometer shall be used to measure the total radiation, that is, direct and diffuse radiations and a pyrheliometer shall be used to measure the direct normal irradiation. Both instruments shall have minimum characteristics as required by the World Meteorological Organization (WMO). These instruments shall be expected to conform with the following specifications:

PERFORMANCE SPECIFICATIONS FOR SOLAR RADIOMETER

	Sensitivity mw/cm	Stability %	Temperature Compensation %	Spectral Selectivity %	Linearity %	Time Constant	Consine Response %
Pyheliometer	± 0.4	± 1.0	± 1.0	± 2.0	± 1.0	<25s	-
Pyranometer	± 1.0	± 1.0	± 1.0	± 2.0	± 1.0	< 5s	±1

The above specifications are for first class instruments and the minimum specifications are described in the following sections.

3.2 Variation in Ambient Temperature: Change of response due to variation in Ambient Temperature can be compensated by providing a built-in temperature compensation circuit with a sensitivity of less than ± 1% over the range of -20 to +40°C (-4 to 104°F).

3.3 Variation in Spectral Response: Pyranometer and Pyrheliometer errors caused by any deviation from the required spectral response of the sensor shall not exceed ± 2% over the range of interest as per WMO specification, ± 1%.

3.4 Nonlinearity of Response: The pyranometer shall have a response within ± 1% of being linear over the range of irradiation existing during the tests. Sometimes the pyranometer is supplied with a calibration curve relating the output to irradiation.

3.5 Time Response: The time constant is defined as the time required for the instrument to achieve a reading of 1 - 1/e = 63.2% of its final reading after a step change in irradiation and it shall be less than five seconds for the pyranometer and less than 25 seconds for the pyrheliometer.

3.6 Variation of Response with angle of Incidence: It is expected that the response of the pyranometer be proportional to the consine of the incident angle of the direct solar radiation and also be constant at all azimuth angles. Any deviation from a true consine response shall be less than ± 1% for the incident angles encountered during the test.

3.7 Effects of Humidity and Moisture: Accumulation of moisture on the surface of the pyranometer or the pyrheliometer, may condense and affect its reading. An instrument with a desiccator that can be inspected is required. The ambient relative humidity and condition of the desiccator should be observed prior to and following any daily measurement sequence.

3.8 Calibration of Instruments: The pyranometer/pyrheliometer shall be calibrated for solar response within 12 months preceding the collector tests against another pyranometer whose calibration uncertainty relative to recognized measurement standards is known. Any change of more than ± 1% over a year period shall warrant the use of more frequent calibration or replacement of the instrument. If instrument is damaged in any significant manner, it shall be recalibrated or replaced.

3.9 Temperature Measurements: The accuracy and precision of the instruments including their associated readout devices shall be within the limits as follows:

	Instrument Accuracy	Instrument Precision
Temperature	± 0.5°C (± 0.9°F)	± 0.2°C (±0.36°F
Temperature Difference	± 0.1°C (± 0.18°F)	± 0.1°C (±18°F)

3.9.1 Temperature Difference Measurement Across the Solar Collector:

The temperature difference of the transfer fluid across the solar collector may be measured with one of the following apparatus:

a) A type T thermopile

b) Calibrated resistance thermometers connected in two arms of a bridge circuit (recommended only when transfer fluid is a liquid).

c) Precision thermometers

d) Calibrated thermistors

e) Calibrated matched type T thermocouples.

Never shall the smallest scale division of the instrument or instrument system exceed 2 times the specified precision. For example, if the specified precision is ± 0.1°C (±0.18°F) the smallest division shall not exceed 0.2°C (0.336°F).

The instrument shall be configured and used in accordance with Chapter IV of this document.

3.10 Liquid Flow Measurements:

The accuracy of the liquid flow rate measurement, using the calibration if furnished, shall be equal to or better than ± 1.0% of the measured value in mass units per unit time.

3.11 Integrator and Recorders:

Strip chart recorders used shall have an accuracy equal to or better than ± 0.5% of the full rate reading and have a time constant of one second or less. The peak signal indication shall be between 50 and 100% of full scale.

Electronic integrators used shall have an accuracy equal to or better than ± 1.0% of the measured value.

The input impedance of recorders shall be greater than 1000 times the impedance of the sensors.

3.12 Air Flow Measurements:

When air is used as the transfer fluid, the air flow rate shall be determined as described in Chapter IV of this document.

3.13 Pressure Measurements:

Pressure measurements in Solar Collectors can be considered in three categories:

(a) Nozzle Throat Pressure - The pressure measured at the nozzle throat shall be made with instruments which shall permit measurements of pressure to within ± 1.0% of the absolute pressure and whose smallest scale division shall not exceed two times the specified reading.

(b) Pressure Drop Across Collector: The static pressure drop across the solar collector shall be measured with a manometer having an accuracy of ± 2.5 Pa (0.01 in. H_2O) for air heating collectors and ± 25 Pa (0.10 in H_2O) for liquid heating collectors.

(b) Air Flow Measurement: The static pressure drop across the nozzle and the velocity pressure at the nozzle throat shall be measured with manometers or pressure transducers which have been calibrated and found to have an accuracy of within ± 1.0% of the reading. The smallest manometer scale division shall not exceed 2.0% of the reading.

3.14.1 Time and Mass Measurements: For calibration purposes, time measurement and mass measurements shall be made to an accuracy of ± 0.2%.

3.15 Wind Velocity:

The wind velocity shall be measured with an instrument and associated readout device that can determine the integrated average wind velocity for each test period to an accuracy of ± 0.8 m/s (± 1.8 mph).

Chapter IV

4 Testing Requirements And The Appropriate Apparatus:

4.1 Collectors with Liquid as Thermal-transfer Fluid: Solar Collectors employing liquid as the thermal transfer fluid shall have a testing configuration similar to the one shown in Figure 1, and especially for natural convection mode of operation.

4.2 Solar Collector shall be rigidly mounted to the test rack at the predetermined tilt angle (for stationary rack). It is important that the test rack, whether fixed or movable, be unaffected by strong gusts of wind.

4.3 Ambient Temperature Sensor shall be housed in a well-ventilated instrumentation shelter with its bottom 1.25 in. (4.1 ft.) above the ground and with its door avoiding direct sun's direct beam. The shelter shall be painted white outside and shall not be closer to any obstruction than twice the height of the obstruction itself.

4.4 Solar Radiation (Irradiation) measurements shall be reported in terms of apparent solar time for the test. A pyranometer shall be used in measuring total radiation and should meet the required specification in Chapter III. The mounting of the pyranometer shall be such that it does not cast any shadow to the collector and to insure that it receives proportionally the same radiation as the collector, it is recommended that it

be mounted near the upper-half periphery of the collector, and in upper center of the collector array. The orientation of the pyranometer should be such its sensor is coplanar with the plane of the collector apperture and also such that its electrical connections are not overheated.

A pyrheliometer shall be used to measure direct radiation and especially for concentrating collectors. To avoid reflected and reradiated irradiation from reaching the sensor of the pyrheliometer, it is recommended that the pyrheliometer be shielded from these irradiations which might originate from below the plane of sensor.

It is important to measure the direct component of the total radiation in which case pyrheliometer would be recommedated.

4.5 Measurement of Temperature Difference (Δ t) across the collector shall be referred to as the temperature difference of the transfer fluid between entering and leaving points of the collector and shall be measured in accordance with Chapter III of this document.

To minimize temperature measurement error, the thermalcouples sensing points shall be insulated from ambient air and have direct connection with the inlet and outlet points of the collector. Both inlet and outlet pipes shall be insulated. It is preferrable that the sensing points of the thermalcouples touch the fluid at both the inlet and outlet points whenever possible.

4.6 Pressure Drop Across the Solar Collector shall be measured using static pressure tap holes and either a manometer or a differential-pressure transducer. The edges of the holes on the inside surface of the pipe should be free of burrs and should not exceed 1.6 mm (1/16 in.) in diameter. The thickness of the pipe wall should be 2.5 times the hole diameter. Provision shall be made for determining the absolute pressure of the entering transfer fluid.

4.7 A storage tank, for convection mode of operation, shall be installed at a given height (H_t), between the top edge of the collector and the bottom side of the tank. The appropriate fluid pressure for the convection mode system is dependent on the height between the collector and the tank and it can be determined by the following formula:

$$H_t = \frac{\text{Volume of water in the Tank (gal)}}{\text{Bottom Area of the Tank (ft}^2\text{)}}$$

Where one gallon of water = 7.48 Ft^3.

4.8. Air Thermal Transfer Fluid is usually used in solar collectors intended for crop drying, space heating, etc. The test configuration is shown in Figure 2 where recommended apparatus are also shown.

4.8.1 Solar Collector Requirements (see Chapter II, Section 2.1.2)

4.8.2 Ambient Temperature Requirements (see Chapter II, Section 2.3.1 (b) and Chapter IV, Section 4.3).

4.8.3 Solar Radiation Requirements (see Chapter III, Section 3.1).

4.8.4 Test Ducts - The air outlet duct between the air flow measuring apparatus and the solar collector shall have the same dimension as the air inlet duct leading to the solar collector.

4.8.5 Measurement of Temperature Difference (Δ t) across the collector can be measured using a thermopile in which case the thermopile shall be made from calibrated thermocouple wire taken from a single spool. The thermocouple wire shall have a diameter no larger than 0.51 mm (24 AWG). There shall be a minimum of six evenly spaced test points in each of the inlet and the outlet ducts of the collector. (see Figure 3).

The temperature sensors shall be connected at the inlet and outlet points, closest to the collector and the inlet and outlet ducts insulated to avoid any loss of more than 0.3°C (0.5°F) between the temperature measuring locations and the collector. Temperature variation during testing at given cross sections of the air inlet test ducts shall be less than $\pm$ 0.5°C (0.9°F) at the location of the temperature sensors. The variation shall be checked prior to testing, and if the variations exceeds the above limits, mixing devices shall be installed to achieve this degree of temperature uniformity.

4.8.6 Temperature measurement will require apparatus of the same standards given in Chapter III, Sections 3.1 and 3.9 where the test points shall be as described in above section, (see Figures 3 and 4).

4.8.7 Duct Pressure Measurements - the static pressure drop across the solar collector shall be measured using a differential pressure measuring

device. Each side of this device shall be connected to externally manifolded pressure taps on the air inlet and air outlet ducts as shown in Figure 4. The pressure taps should consist of 6.4 mm. (0.25 in) nipples soldered to the duct and centered over 1 mm (0.04 in.) diameter hole. The edges of these holes on the inside surfaces of the ducts should be free of burrs and other surface irregularities.

4.8.8 Air Flow Measuring Apparatus. Where the air flow rate is sufficiently large, it shall be measured with the nozzle apparatus shown in Figure 5. This apparatus consists basically of a receiving chamber, a discharge chamber and an air flow measuring nozzle. The distance from the center of the nozzle to the side walls shall not be less than 1.5 times the nozzle throat diameter, and the diffusion baffles shall be installed in the receiving chamber at least 1.5 nozzle throat diameters upstream of the nozzle and 2.5 nozzle throat diameters downstream of the nozzle. The apparatus should be designed so that the nozzle can be easily changed and the nozzle used on each test shall be selected so that the throat velocity is between 15 m/s (2960 fpm) and 35 m/s (6900 fpm). When nozzles are constructed in accordance with Figure 6 and installed in accordance with this section of this standard, the discharge coefficient may be assumed to be as follows:

Reynolds Number (N_{Re})	Discharge Coefficient C_n
20,000	0.96
50,000	0.97
100,000	0.98
150,000	0.98
200,000	0.99

If the throat diameter of the nozzle is 0.13m (5 in.) or larger, the discharge coefficient may be assumed to be 0.99. For nozzles smaller than 0.05 m (2 in.) and where a more accurate discharge coefficient than given above is desired, the nozzle should be calibrated. The area of the nozzle shall be determined by measuring its diameter to an accuracy of $\pm$ 0.2% in four places approximately 45 degrees apart around the nozzle in each of the two planes through the nozzle throat, one at the outlet and the other in the straight section near the radius.

Where the nozzle apparatus is used, an exhaust fan capable of providing the desired flow rates through the solar collector shall be installed as shown in Figure 2. The velocity of the air passing through the nozzle shall be determined by either measuring the velocity head by means of a commercially available pilot tube or by measuring the static pressure drop across the nozzle with a differential pressure measuring device. If the latter method is used, one end of the device shall be connected to a static pressure tap located flush with the inner wall of the discharge chamber, or preferably, several taps in each chamber should be manifolded to single device.

Where the air flow rate is sufficiently small so that a nozzle constructed and installed in accordance with the requirements above would have a throat diameter of smaller than 0.025 m (1 in.), the above configuration should not be used and the air flow measuring apparatus shown in Figure 2 should consist of a calibrated flow element where at least 10 pipe diameters of upstream and downstream pipe section have been included in the calibration. This calibration is essential because, for small flow elements, the discharge coefficients associated with such

elements vary considerably from those associated with the large elements. In addition, for small pipe or duct sizes, the ratio of pipe circumference to pipe area becomes large and the characteristics of the upstream and downstream pipe sections affect the behavior of the element itself.

4.8.9 Air Leakage shall be minimized by taping and sealing all joints. Extreme caution is needed because small leakage rates can have significant effects on test results.

4.8.10 Air-Reconditioning Apparatus shall control the dry bulb temperature of the transfer medium entering the solar collector to within ± 1.0°C (± 1.8°F) of desired test values at all times during the tests. Its heating and cooling capacity shall be selected so that the dry bulb temperature of the air entering the reconditioning apparatus may be raised or lowered to the required amount to meet the applicable test conditions in Section 4.8.8 of this Chapter.

Chapter V.

5 Test Procedures and Computations:

5.1 Thermal Performance:

In general, the thermal performance of the solar collector is determined in part by obtaining values of instantaneous efficiency for a combination of values of incident radiation, ambient temperature, and inlet fluid/air temperature. This requires one to experimentally measure the rate of incident solar radiation onto the collector as well as the rate at which the energy is being conducted to the transfer fluid as it passes through the collector, all under steady state or quasi-steady state conditions. In addition, tests are performed to determine the time response characteristics of collector as well as how its steady state thermal efficiency varies with the incident angle between the direct beam and the collector.

5.2 Basic Performance Equations:

The performance of a flat plate solar collctor operating under steady state conditions can be described as:

$$\frac{Q_u}{A_a} = I_t(\tau\alpha)_e - U_L\ (t_p - t_a) = \frac{\dot{m}}{A_a} C_p\ (t_{f,e} - t_{f,i}) \qquad .....(5.1)$$

Modifying Eqn. (5.1) we get:

$$\frac{Q_u}{A_a} = I_{DN}\ (\tau\alpha)_e\ \rho\Gamma - U_L \frac{A_r}{A_a} (t_r - t_a) = \frac{\dot{m}}{A_a} C_p\ (t_{f,e} - t_{f,i}) \qquad .....(5.2)$$

We now introduce a new and more explicit parameter F_R, which can be described as:

$$F_R = \frac{\text{actual useful energy collected by a flat-plate collector}}{\text{useful energy collected if the entire flate-plate collector surface were at the inlet fluid temperature}}$$

Introducing this factor into eqn. (5.1) we get:

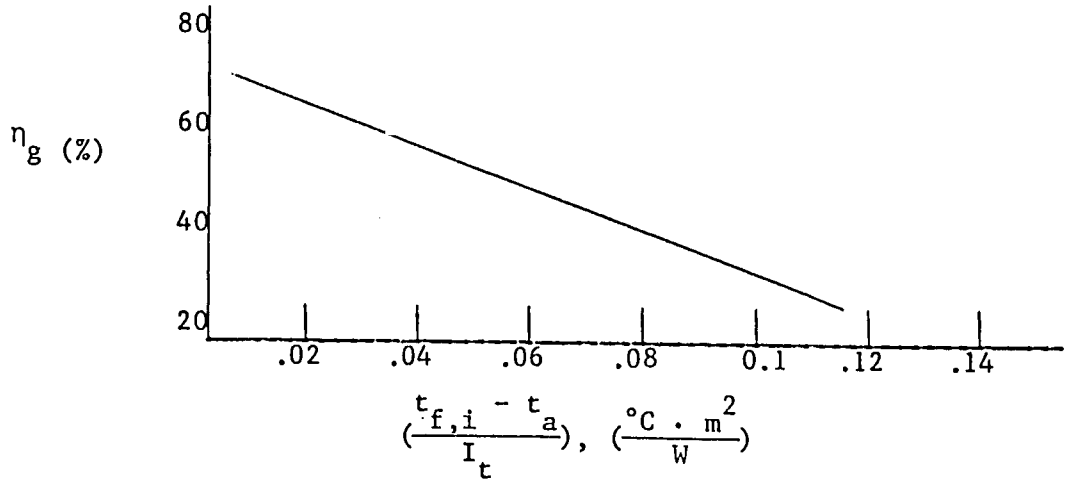
$$\frac{Q_u}{A_a} = F_R\,[I_t\,(\tau\alpha)_e - U_L\,(t_{f,i} - t_a)] = \frac{\dot{m}}{A_a}\,C_p\,(t_{f,e} - t_{f,i}) \qquad .....(5.3)$$

Now let us define the solar collector efficiency as:

$$\eta_g = \frac{\text{actual useful energy collected}}{\text{solar energy incident upon or intercepted by the collector}} = \frac{Q_u/A_g}{I_t} \qquad .....(5.4)$$

Therefore efficiency of the flat collector plate can be given as:

$$\eta_g = (A_a/A_g)\,F_R\,\left[(\tau\alpha)_e - U_L\,\frac{(t_{g,i} - t_a)}{I_t}\right] = \frac{\dot{m}C_p\,(t_{f,e} - t_{g,i})}{A_g\,I_t} \qquad .....(5.5)$$



Here, U_L is not a constant but rather a function of the temperature of the collector and the ambient weather conditions. Also the product $(\tau\alpha)$ rises with the incident angle between the solar beam and the collector.

Although a straight-line representation of the efficiency curve will suffice for many flat plate solar collectors, some flat-plate collectors and most concentrating collectors require the use of a higher-order-fit, i.e., a second order polynomial, due to variation of U_L with receiver temperature.

5.2.1 Collector Time Constant, $KC_A/\dot{m}C_p$, can be used to determine the time response of the solar collector in order to be able to evaluate the transient behavior of the collector, and to select the proper time intervals for the quasi-steady state efficiency tests.

Whenever transient conditions exist, the equalities defined by Eqns. (5.1), (5.2) and (5.3) do not govern the thermal performance of the collector since part of the solar energy absorbed is used for heating up the collector and its components. Therefore the proper equation for the transient behavior of a solar collector can be given as:

$$\frac{C_A}{A_g}\frac{dt_f}{dT} = F_R I_t (\tau\alpha)_e - F_R U_L (t_{f,i} - t_a) - \frac{\dot{m}C_p}{A_g}(t_{f,e} - t_{f,i}) \quad .....(5.6)$$

By considering a number of assumptions in the transient eqn. (5.6) a solution for the exit temperature can be calculated from the same eqn. thus:

(a) Assume that the solar radiation I_t or inlet fluid temperature $t_{f,i}$ or both I_t and $t_{f,i}$ are suddenly changed and held constant,

(b) Also assume that $(\tau\alpha)_e$, U_L, t_a, $\dot{m}$ and C_p are constant for transient period,

(c) Lastly, assume that the rate of change of the transfer fluid exit temperature with time related to the rate of change of transfer fluid average temperature with time such that;

$$\frac{dt_f}{dT} = K\frac{dt_{f,e}}{dT} \quad .....(5.7)$$

where $$K = \frac{\dot{m}C_p}{F'U_L A_a}\left[\frac{F'}{F_R} - 1\right] \quad .....(5.8)$$

and $F' = \dfrac{\text{actual useful energy collected by flat-plate collector}}{\text{useful energy collected if the entire flat-plate collector surface were at the average fluid temperature}}$

Now we can solve equation (5.6) to give the exit temperature of the fluid as a function of time. Thus,

$$\frac{F_R\, I_T\, (\tau\alpha) - F_R\, U_L\, (t_{f,i} - t_a) - (\dot{m}C_p/A_a)(t_{f,e,T} - t_{f,i})}{F_R\, I_T\, (\tau\alpha) - F_R\, U_L\, (t_{f,i} - t_a) - (\dot{m}C_p/A_a)(t_{f,e,initial} - t_{f,i})} = e^{-[\dot{m}C_p/KC_A]T} \qquad \ldots\ldots(5.9)$$

The term $KC_A/\dot{m}\, C_p$ in the above equation (5.9) is <u>the time constant</u> and is the time required for the quantity on the left side of the same equation (5.9) to change from 1.0 to 0.36 where 0.368 = 1/e.

5.2 3 <u>Collector Incident Angle Modifier:</u> The incident angle modifier, $K_{\alpha\tau}$, can be introduced into equations (5.1), 5.2), (5.3) and (5.4) by replacing the effective transmittance-absorptance factor ($\tau\alpha$) by the value at normal incidence, ($\tau\alpha$)$_{e,n}$, provided that another factor called the incident angle modifier $K_{\alpha\tau}$ is introduced. Equation (5.4) then becomes:

$$\eta = (A_a/A_g)\, F_R\, [K_{\alpha\tau}(\tau\alpha)_{e,n} - U_L\, \frac{(t_{f,i} - t_a)}{I_t}] = \frac{\dot{m}C_p}{A_g I_t}(t_{f,e} - t_{f,i}) \qquad \ldots\ldots(5.10)$$

It can be shown that for variety of solar collectors, ($\tau\alpha$) should vary with incident angle according to the expression:

$$(\tau\alpha)_e = a - \frac{b}{\cos\theta} \qquad \ldots\ldots(5.11)$$

Comparing equation (5.10) and (5.11) we see that

$$K_{\alpha\tau}(\tau\alpha)_{e,n} = a - \frac{b}{\cos\theta} \qquad \text{.....(5.12)}$$

Solving for $K_{\alpha\tau}$ and taking $(\tau\alpha)_{e,n} = a - b$, we get

$$K_{\alpha\tau} = 1 - \frac{b}{a-b}\left(\frac{1}{\cos\theta} - 1\right) \qquad \text{.....(5.13)}$$

Thus, in terms of one constant

$$K_{\alpha\tau} = 1 - b_o\left(\frac{1}{\cos\theta} - 1\right) \qquad \text{.....(5.14)}$$

The significance of the incident angle modifier to the test procedures outlined herein is that the thermal efficiency values are determined for the collector at or near normal incidence conditions. Therefore, the y intercept of the efficiency curve is equal to $(A_a/A_g)\ F_R\ (\alpha\tau)_{e,n}$. A separate test is conducted to determine the value of $K_{\alpha\tau}$ so that the performance of the collector can be predicted under a wide range of conditions and/or time of day using equation (5.10).

5.3 <u>Testing Procedures for Performance Parameters:</u> Now that we have discussed the determination of the various general parameters involved in the evaluation of the performance of a solar collector, we can now discuss the testing procedures for these parameters.

The first parameter test to be conducted shall be the determination of the <u>collector time constant</u>. The method for conducting this test is

discussed in, Section 5.3.1. On completion of this test, a series of thermal efficiency tests is conducted as discussed in, Section 5.3.2. After the two above tests are conducted, a final test to determine the incident angle shall be conducted as explained in Section 5.3.3. It should be mentioned here that the incident angle modifier test is not necessary for those flat-plate collectors for which the angular response characteristics are known; included in this category are the single and multiple covered flat-plate collector without reflectors, honey comps, convection bafflers, selective surface with directional characteristics, etc.

5.3.1 Experimental Determination of the Collector Time Constant: There are two methods for testing the solar collector time constant:

(1) In one of these methods, the inlet temperature of the transfer fluid, $t_{f,i}$, is adjusted as closely as possible to the ambient temperature $\pm$ 1°C ($\pm$ 1.8°F) while circulating the transfer fluid through the collector at the flow rate specified in Section 5.3.2 and maintaining steady state or quasi-steady state conditions with an incident solar flux of greater than 790 W/m^2 (250 Btu/hr.ft^2). The incident solar energy is

then abruptly reduced to zero by either shielding the collector from the sun by turning the collector away from the sun tilt angle (on a movable mount) and/or shading with white, opaque cover. The cover should be suspended off the surface of the collector so that ambient air is allowed to pass over the collector as prior to the beginning of the transient test. The temperatures of the transfer fluid at the inlet, $t_{f,i}$, and outlet, $t_{f,e}$, are continuously monitored as a function of time until:

$$\frac{t_{f,e,T} - t_{f,i}}{t_{f,e,initial} - t_{f,i}} < 0.30 \qquad \text{.....(5.14a)}$$

(2) In the second method for testing solar collector time contant, the collector is shielded from the sun as specified above, or tested at night, or tested indoors without the use of a solar simulator. The inlet temperature of the transfer fluid is maintained at 30°C (54°F) above the ambient temperature, while circulating the transfer fluid through the collector at the flow rate specified in Section 5.3.2, for a period of time sufficient to establish a constant outlet temperature, $t_{f,e}$. After equilibrium is reached, the inlet temperature, $t_{f,i}$, is abruptly reduced as near as possible to within $\pm$ 1°C (1.8°F) of the ambient temperature. The temperature of the transfer fluid at the inlet, $t_{f,i}$ and outlet $t_{f,e}$, are continuously monitored as a function of time until:

$$\frac{t_{f,e,T} - t_{f,i}}{t_{f,e,initial} - t_{f,i}} < 0.30$$

For either method, the actual time constant is the time T required for the quantity:

$$(t_{f,e,T} - t_{f,i}) \ / \ (t_{f,e,initial} - t_{f,i}) \text{ to change}$$

from 1.0 to 0.368.

5.3.2 Experimental Determination of the Collector Thermal Efficiency:

The thermal efficiency of a solar collector shall be conducted in such a way that a governing efficiency curve for the near normal incidence is determined for the collector under test conditions described in Sections 5.5 and 5.8. At least four different values of inlet temperatures shall be used to obtain the value of $\Delta t/I_t$. An acceptable distribution of inlet temperatures for flat-plate collectors is to set the Δt at 10, 30, 50 and 70% of the stagnation temperature rise obtained at the given conditions of solar intensity and ambient air temperature.

At least four data points shall be taken for each value of $t_{f,i}$; two during the time period preceding solar noon and two in the period following solar noon, the specific periods being chosen so that the data points represent times symmetrical to solar noon. This later requirement is made so that any transient effects that may be present will not bias the test results when they are used for design purposes. The requirement for obtaining data points equally divided between morning and afternoon is not mandatory when testing with an altazimuth mount. It is necessary to plot curves by data points that represent efficiency values determined by integrating the data over a time period equal to the time constant, determined in accordance with, Sections 5.3.1 and 5.3.4 or five minutes,

whichever is larger. The integrated value of incident solar energy will be divided into the integrated value of energy obtained from the collector to obtain the efficiency value for the test period.

When a normal-incidence altazimuth mount is used for the tests outside, the time interval specified above may be reduced to five minutes or 1/2 the time constant of the collector, whichever is larger.

To ensure that the incident solar radiation is steady for each time interval during which an efficiency value is calculated, either electronic integrators or continuous pen strip chart recorder may be used to determine the integrated values of incident solar radiation and temperature rise across the collector.

Pyranometers and Pyrheliometers shall be kept out of wetness, and frequently checked to avoid any accumulation of water vapour in the glass cover. Also, both the collector glazings and the pyranometers/ pyrheliometers shall be carefully dusted off to avoid any scratches while at the same time removing any dust that might distract normal solar radiation.

It is necessary that the transfer fluid be circulated through the collector at the appropriate inlet temperature level until the temperature has remained constant for 15 minutes prior to the period in which data shall be taken for the calculation of the efficiency values.

For <u>indoor simulator testing laboratory</u>, the procedure shall be as follows:

--the transfer fluid shall be circulated through the collector at the inlet temperature chosen for the test.

--after equilibrium is established, the simulator is turned on and the desired radiation obtained by adjusting the lamp voltage. The flow rate of the transfer fluid should be maintained at a standardized value for all data points. The recommended value of flow rate per unit area for tests are 0.02 kg/sec. m^2 (14.7 lb.m/hr. ft^2) when a liquid is the transfer fluid and 0.01 m^2/sec. m^2 (2 cfm/ft^2) of standard air when air is used as the heat transfer medium. It can be noted here that for air heaters, efficiency is much more a function of flow rate than with collectors using liquid transfer fluid. Because of this importance of flow rate in air heat transfer collectors, it is recommended that a second test sequence using 0.03 m^2/sec. m^2 (6 cfm/ft^2) be performed.

Nonetheless, if a particular collector design has specified a particular fluid flow rate, then the specified flow shall be used for testing the collector.

5.3.3 <u>Experimental Determination of Collector Incident Angle Modifier for Stationary Collectors:</u> The determination of incident angle modifier can be tested in two ways:

(1) One of the methods to determine the incident angle modifier is for the indoor testing where solar simulator is used or outdoor testing where orientation is controlled by adjustable and movable test rack. In this method, four separate efficiency values are determined in accordance with Section 5.3.2 above. The collector is oriented so that the average incident angles

between it and the direct solar radiation for the four test conditions are respectively, approximately 0, 30, 45 and 60 degrees.

(2) For the second method of determining the incident angle modifier, outside permanent testing rack is used, where the collector orientation cannot be arbitrarily adjusted with respect to the direction of incident solar radiation. In this method, six separate efficiency values are determined in accordance with the method described in Section 5.3.2 above. The efficiency values are determined in three pairs, where each pair includes a value of efficiency early in the day and a second value late in the day. The average incident angle between the collector and the solar beam for both data points is the same. The efficiency of the collector for the specific incident angle shall be considered equal to the average of the two values. As with the first method, data shall be collected for average incident angles of approximately 0, 30, 40 and 60 degrees.

5.4.1 Computation of Collector Time Constant:

Earlier on in equation (5.9), we defined the collector time constant as that time required to bring the value of the parameters in the left side of equation (5.9) to equal 0.368. Now we will define further the experimental procedure to compute this value:

--the incident solar radiation is equal to zero by holding the inlet fluid temperature equal to the ambient temperature $(t_{f,i} - t_a) = 0$.

--by monitoring the entering and exit fluid temperatures as a function of time, then the time constant is the time required for:

$$\frac{t_{f,e,T} - t_{f,i}}{t_{f,e,initial} - t_{f,i}} = 0.368 \qquad .....(5.15)$$

In the case where fluid temperature cannot be controlled to equal ambient air temperature, within $\pm$ 1°c ($\pm$ 1.8°F), an estimate of the product $(A_a/A_g)\ F_R\ U_L$ should be made for the collector under the testing conditions such that the calculated time constant will be the time required for:

$$\frac{(A_a/A_g)\ F_R\ U_L\ (t_{f,i} - t_a) + \frac{\dot{m}C_p}{A_g}\ (t_{f,e,T} - t_{f,i})}{(A_a/A_g)\ F_R\ U_L\ (t_{f,i} - t_a) + \frac{\dot{m}C_p}{A_g}\ (t_{f,e,initial} - t_{f,i})} = 0.368 \qquad .....(5.16)$$

5.4.2 Computation of Collector Thermal Efficiency:

The efficiency of the collector is calculated for every test interval data point using the equation:

$$\eta = \frac{\dot{m}C_p \int_{T_1}^{T_2} (t_{f,e} - t_{f,i})\, dT}{A_g \int_{T_1}^{T_2} I\, dT} \qquad .....(5.17)$$

For concentrating collectors, which accept direct radiation only, the computation should be done twice, once with the total irradiation, I_t, as denominator of equation (5.17), and once with the direct irradiation, I_D.

For flat-plate collectors I_t is used.

The conventional efficiency curve does not consider some important parameters such as -- fluid flow rate; wind velocity, inclination angle and the average collector temperature. For this reason a more meaningful evaluation of collector efficiency is necessary. However, the following procedure for evaluating collector efficiency should be satisfactory for the time being:

1) Test the efficiency of the collector for all local weather conditions taking into account:

a) heat transfer fluid velocity

b) wind velocity

c) Orientation

d) Inclination angle

2) Daily efficiency for a number of different days:

a) η_{clear} - for 5 clear days

b) η_{cloudy} - for 5 cloudy/rainy days

c) $\eta_{semiclear}$ - for 5 semiclear days

d) η_{total} - average irradiation for the 15 days.

(3) $$\bar{\eta} = \frac{\bar{\eta}_a + \bar{\eta}_b + \bar{\eta}_c + \bar{\eta}_d}{4} \qquad (5.18)$$

5.4.3 Computation of Collector Incident Angle Modifier:

The inlet fluid temperature is held sufficiently close to ambient temperature so that $(t_{f,i} - t_a) \simeq 0$, then three different values of incident angle are determined. From these conditions, it will be found that the relationship between $K_{\alpha\tau}$ and the efficiency can be written as

$$K_{\alpha\tau} = \frac{\eta_g}{(A_a/A_g)\ F_R\ (\tau\alpha)_{e,n}} \qquad (5.19)$$

We have already demonstrated that $(A_a/A_g)\ F_R\ (\tau\alpha)_{e,n}$ intercepts the Y - axis of the efficiency curve, see equation (5.5). Therefore the three different values of $K_{\alpha\tau}$ can be computed for the different incident angles using equation (5.19).

In the case where the inlet fluid temperature cannot be controlled to equal the ambient air temperature, within $\pm$ 1°C (1.8°F), then an estimate of $(A_a/A_g)\ F_R\ U_L$ product should be made for the collector for the conditions of the test and each value of $K_{\alpha\tau}$ computed as:

$$K_{\alpha\tau} = \frac{\eta_g + (A_a/A_g)\ F_R\ U_L\ (t_{f,i} - t_a)/I}{(A_a/A_g)\ F_R\ (\alpha\tau)_{e,n}} \qquad .....(5.20)$$

where $I = I_t$ for collectors accepting total radiation

and $I = I_D$ for collectors accepting only direct radiation.

5.4.4 Computation of Air Flow Rate:

For collectors using air as the heat transfer medium, the air flow rate through the nozzle can be calculated using the following equations.

$$Q_{mi} = 1.41\ C_n\ A_n\ (P_v\ V'_n)^{0.5}$$

$$V'_n = 10.1 \times 10^4 V_n/P_n\ (1 + W_n) \qquad .....(5.21)$$

and the air flow rate of standard air is therefore:

$$Q_s = Q_{mi}/\ (1.2\ V'_n) \qquad .....(5.22)$$

5.4.5 Computation of Nozzle Reynolds Number:

The Reynolds number can be calculated as:

$$N_{Re} = f_t\ V_a\ D_n \qquad .....(5.23)$$

The temperature factor for air are shown in the following Table:

TEMPERATURE °C	TEMPERATURE °F	FACTOR F_t
-6.7	20	78275
+4.4	40	72075
+15.6	60	67425
+26.7	80	62775
+37.8	100	58125
+48.9	120	55025
+60.0	140	51925
+71.1	160	48825

4.4.6 Computation of Theoretical Power Requirements:

It might be necessary to determine the power required to move the transfer fluid through the collector. This can be accomplished by use of the following equation:

$$P_{th} = \dot{m} \cdot \Delta P/W$$

Chapter VI

Conclusions

So far we have described all the ideal/theoretical parameters and procedures for the solar thermal heating systems. Some of these parameters are not vital to the general performance of the systems and especially the pressure test which is necessary for large systems and also for all systems designed for high temperatures. Since the solar collector designs existing in Kenya are designed for low temperatures, below boiling point, a simpler testing procedure, describing the most critical parameters, is necessary as a first step in the development of the testing laboratory. Nonetheless, the final goal should be to develop testing facilities capable of testing all the parameters as described in chapters one to five. The purpose of developing a first step facility is to avoid high cost and at the same time allow for a gradual growth of personnel training and experience.

As is evidenced from the efficiency formula, eqn. (5.5), initial parameters of the solar thermal heating systems are those determining the overall ability of the collector to conduct and transfer solar energy to the heat transfer fluid. Considering the terms appearing in the efficiency formula, it can be seen that the measurable parameters are: temperature difference $[(t_{f,e} - t_{f,i}) = \Delta t]$, fluid flow rate ($\dot{m}$), gross collector area (A_g), and the total solar irradiation falling on the collector aperture (I_t). Values for the specific heat (C_p) are available in tables which are provided by the manufacturers of the fluids, upon request. Also the fluid flow rates are provided by the collector manufacturers in the manual as per Kenya Standard Guidelines for Solar Water Heater Systems.

The effectiveness of these parameters can be tested by following the test procedures described in Chapter Two, Sections 2.1, 2.5, 2.6, 2.7 and 2.8. The tests for pressure and thermal shocks could be needed in larger systems and may be left out in the first test facility development stage. However, test development plans should project the inclusion of these tests as soon as finance and qualified personnel become available.

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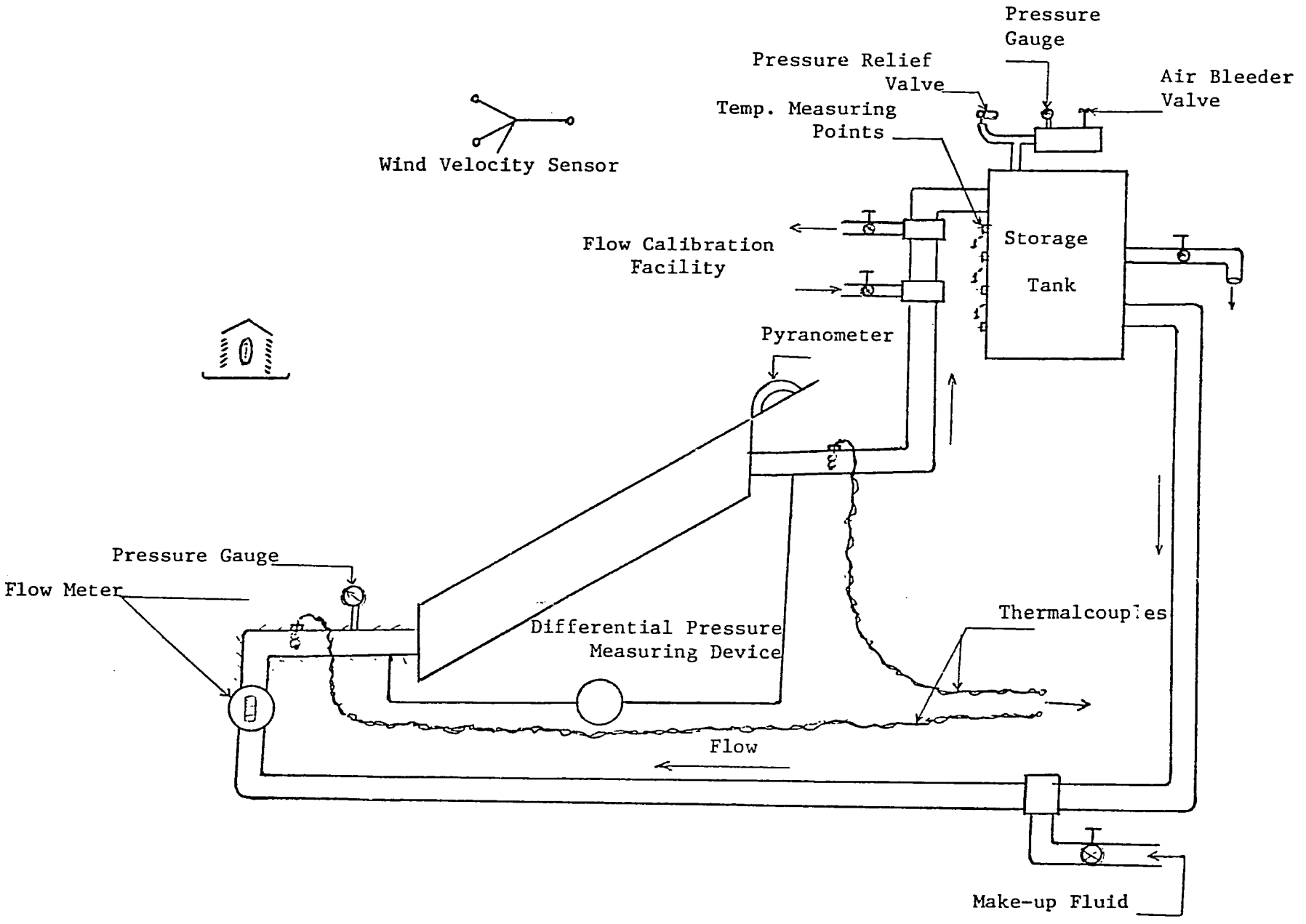


Fig. 1 Natural Convection Collectors Testing Configuration

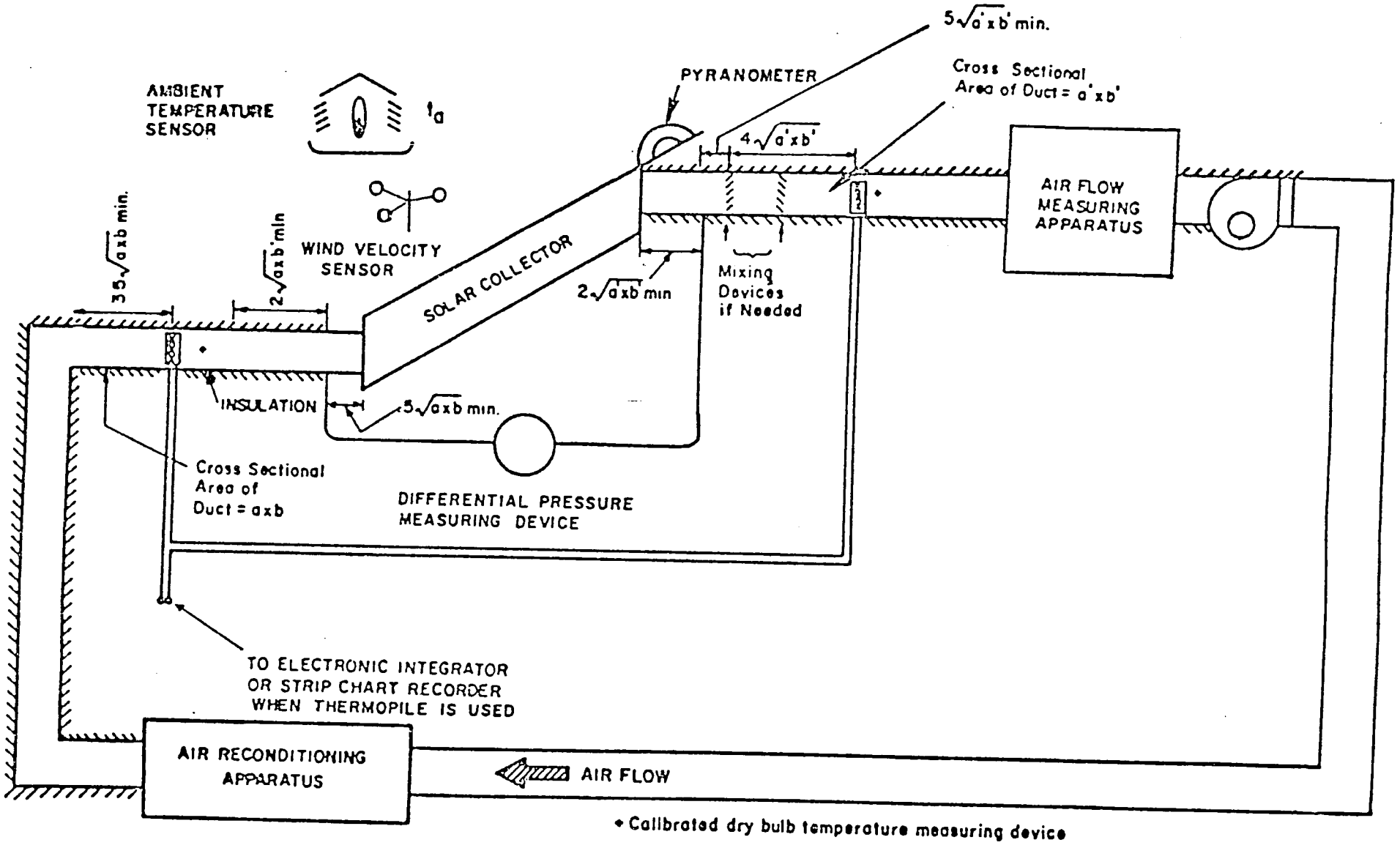


Fig. 2 Testing Configuration for the Solar Collector when the Transfer

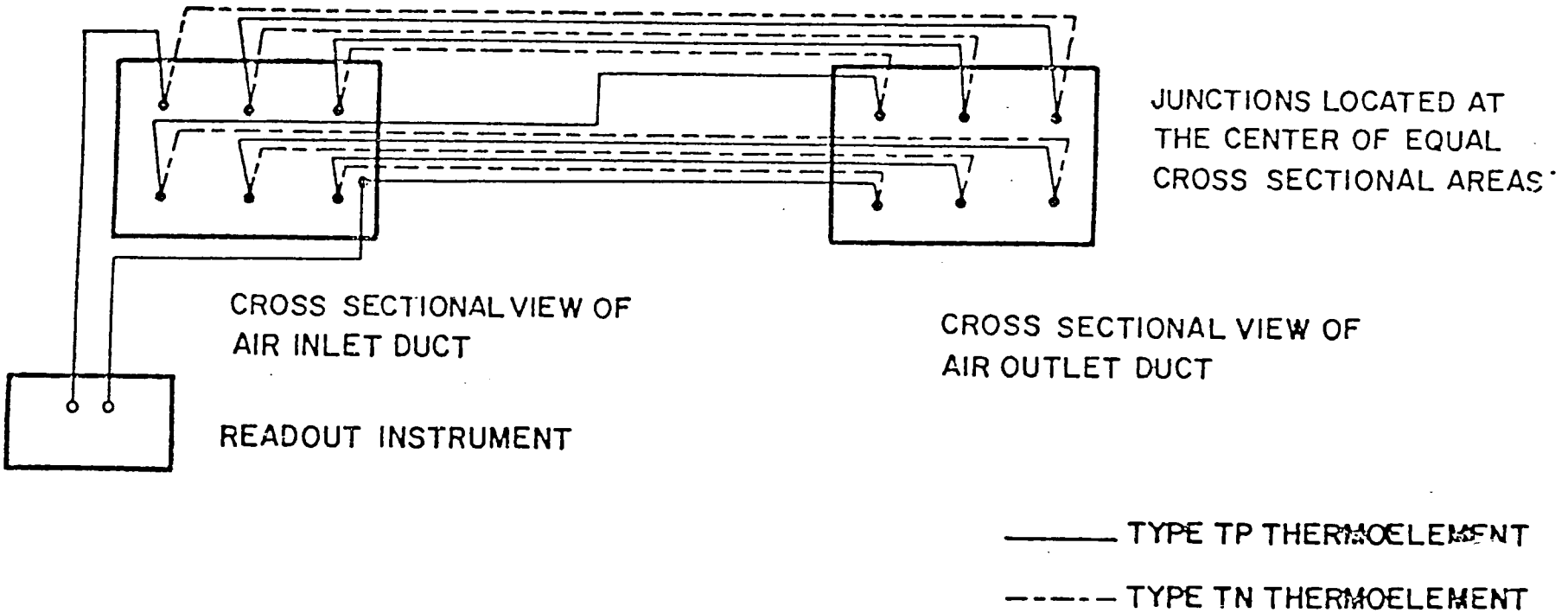


Fig.3 Schematic of the Thermopile Arrangement Used to Measure the Temperature Difference Across the Solar Collector

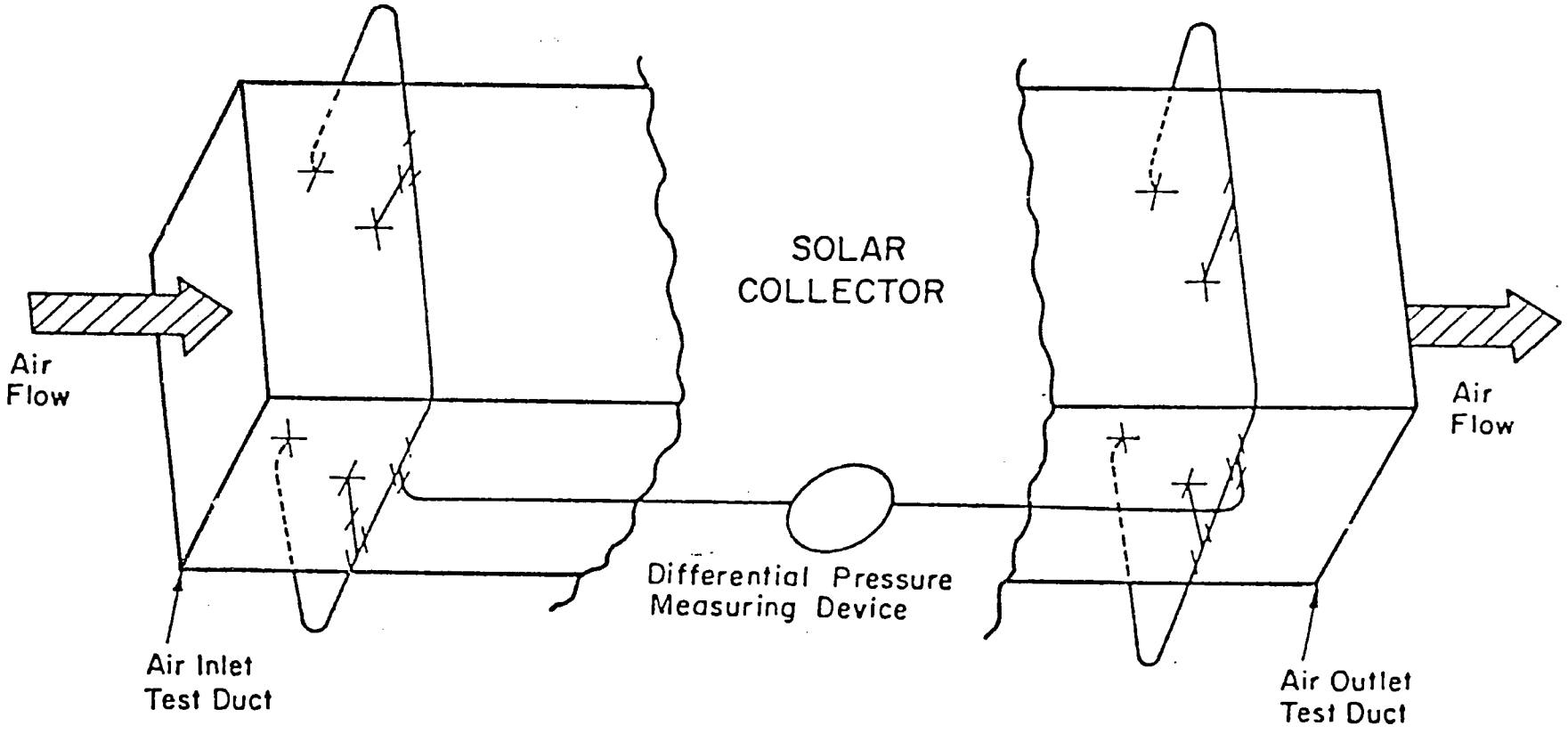
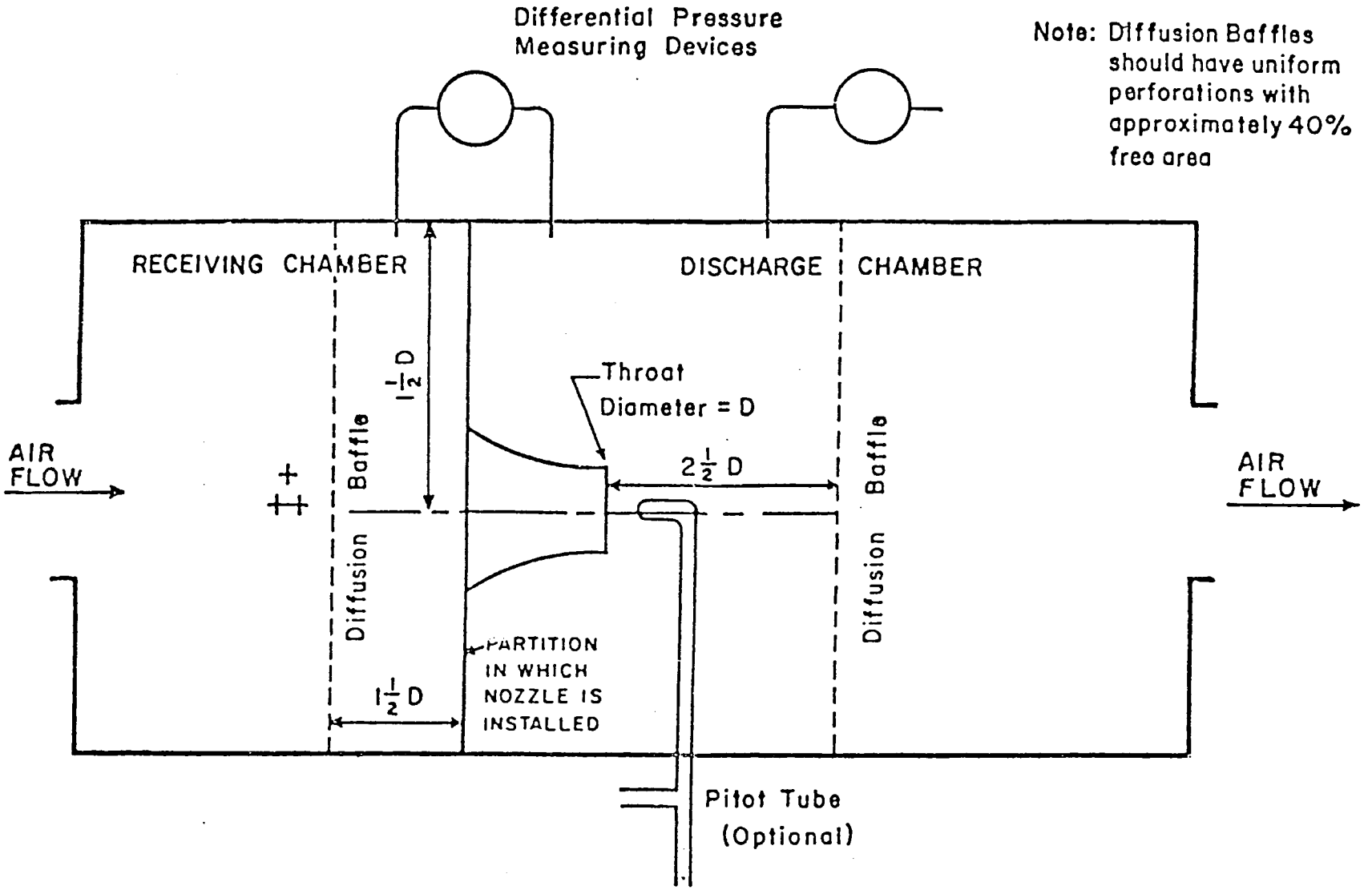


Fig. 4 Schematic Representation of the Measurement of Pressure Drop Across the Solar Collector when Air is the Transfer Fluid



+ CALIBRATED DRY BULB TEMPERATURE MEASURING DEVICE

++ CALIBRATED WET BULB TEMPERATURE MEASURING DEVICE

Fig. 5 Nozzle Apparatus for Measuring Air Flow Rate

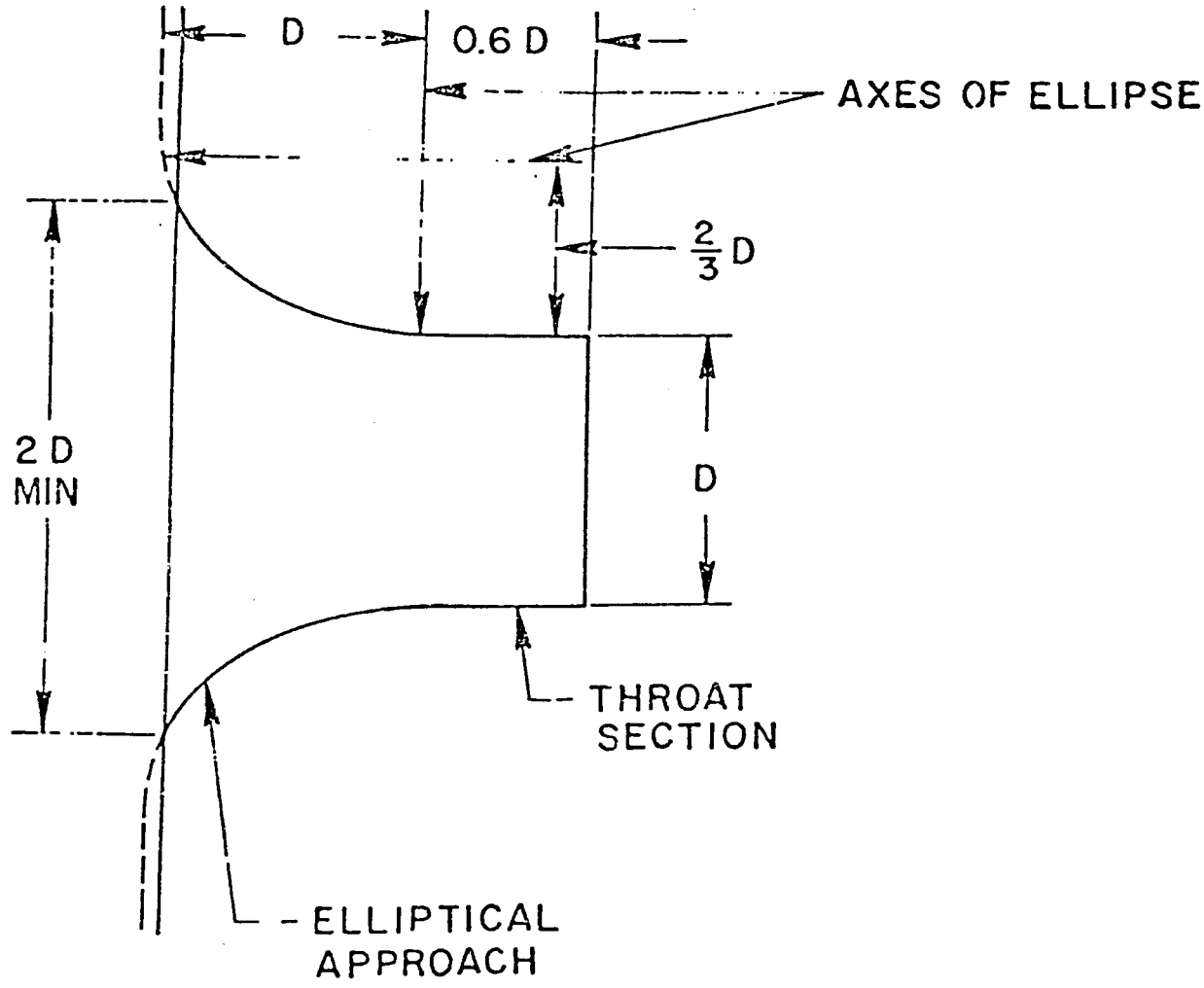


Fig. 6 Air Flow Measuring Nozzle