MASTER

C00-4522-1

EXPERIMENTAL INVESTIGATION OF AN INEXPENSIVE SKY TEMPERATURE MEASURING DEVICE

Final Report
for Period June 1, 1977-June 30, 1979

S. Karaki and P. Brothers

Solar Energy Applications Laboratory
Colorado State University
Fort Collins, Colorado 80523

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

August 1979

Prepared for

THE UNITED STATES DEPARTMENT OF ENERGY
UNDER CONTRACT NO. EG-77-S-02-4522.M003

ce
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
2. STATEMENT OF THE PROBLEM	1
3. THEORETICAL CONSIDERATIONS	2
4. DETERMINATION OF THE SKY TEMPERATURE	4
5. CONSTRUCTION OF THE DEVICE	5
6. MEASUREMENTS	7
7. DISCUSSION	9
8. CONCLUSIONS	9
9. ACKNOWLEDGEMENTS	10
REFERENCES	11
APPENDIX	12

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Device for Measurement of Sky Temperature	6
2	Typical Temperatures Measured with the Experimental Device and a Barnes Radiometer	8

ABSTRACT

The objectives were to develop a simple approach for determining clear sky temperature from ground air temperature and absolute humidity and to develop an inexpensive device for direct measurement of sky temperature. The analytical approach taken was similar to that developed by Bliss. A simpler model to estimate sky temperature to acceptable accuracy, however, was not achieved. A simple device to measure sky temperature was designed and tested but development efforts within the means of the project were unsuccessful. It was concluded that a device that could include measurement or knowledge of the convective heat transfer coefficient rather than control or elimination of it would be an alternative approach in the development of a sky temperature measurement device. Project funds were depleted before the alternative device could be designed and tested.

MEASUREMENT OF SKY TEMPERATURE

1. INTRODUCTION

Long wave radiative heat loss to the atmosphere is an important mechanism in many areas of thermal performance. It is significant in the energy balance of flat plate collectors, buildings, or bodies of water, for example. However it is often difficult to quantify, due to a lack of knowledge of the incoming atmospheric radiation. This study was undertaken in an attempt to provide an inexpensive device for the measurement of this component of the energy balance.

2. STATEMENT OF THE PROBLEM

For a body, exposed to the atmosphere, at night-time, the energy balance can be written as follows:

$$\begin{aligned}\text{Net heat flux} &= \text{radiation in from atmosphere} \\ &\quad - \text{radiation out from body} \\ &\quad + \text{thermal communication with the immediate} \\ &\quad \quad \text{environment (i.e. conduction, convection)}\end{aligned}$$

$$\begin{aligned}\text{or, } Q'' &= \text{radiation from atmosphere} \\ &\quad - \sigma \epsilon T^4 \\ &\quad + h(T_a - T)\end{aligned}\tag{1}$$

where heat flow is positive into the body, and

Q'' is the net heat flux

σ is the Stefan-Boltzmann constant

T is the temperature of the body

ϵ is the emissivity of the body

T_a is the ambient temperature

h is a heat transfer coefficient

The term for the radiation from the atmosphere has typically been presented in one of two ways. In the first, the sky has been regarded as a black body radiator, with a "sky temperature" T_s such that the radiation flux incident upon the earth's surface is given by σT_s^4 .

The other approach is to consider the atmosphere as being a radiative source at the ambient temperature T_a , with an apparent emissivity ϵ_s such that the radiation flux incident upon the earth's surface is given by $\sigma \epsilon_s T_a^4$.

Here we are using the first concept. This gives the formula

$$\dot{Q}'' = \sigma T_s^4 - \sigma \epsilon T^4 + h(T_a - T) \quad (2)$$

Our problem is then to measure the incoming radiation from the atmosphere; i.e. to determine the "sky temperature" T_s .

3. THEORETICAL CONSIDERATIONS

Atmospheric radiation is long-wave radiation (from 3 to 100 μ m), and comes principally from the water vapor and carbon dioxide in the atmosphere, with water vapor being much more important of the two.

A number of mathematical models have been postulated to estimate atmospheric radiation under clear sky conditions. The models are based on knowledge of the ambient temperature at ground level [1,2], or this

quantity together with the vapor pressure of water at ground level [3,4,5]. When compared with actual measurements, these models have given results ranging from excellent agreement [6] through adequate agreement [7] to showing large differences [8]. The accuracy with which the model can be used to predict sky temperature appears to depend on location and local empirical constants; there exists no universal formula that is applicable for all situations and all locations.

Work has also been done on predicting the radiation under cloudy conditions [9,10]. These approaches involve the calculation of a correction factor to the empirical formulas referenced above.

Initially, as part of this project, it was intended to develop an equation for calculating the clear sky temperature from the ground level temperature and absolute humidity. This correlation was to be based on some earlier work of the project leader on the mass-weighted average atmospheric temperature [11]. However investigation of this concept showed little promise of success. All logical developments led to duplication of earlier work, especially that by Bliss [3]. Much of the work in this project was concentrated on development of a "low-cost" instrument to measure sky temperature.

The mass-weighted average atmospheric temperature is obtained by assuming gradients for the variation with altitude of the temperature and density of air, and manipulating these to obtain a weighted average. Bliss' work (3) considers the presence in the atmosphere of water vapor and carbon dioxide, these being the principal sources of atmospheric radiation. Using experimental data for the emissivities of these substances as a function of pressure and temperature, and experimental

data for the variation with altitude of their concentration, Bliss is able to determine the atmospheric radiation. His results are presented as a series of curves giving the sky temperature as a function of the air temperature near the ground and the dewpoint.

Much of the work in this project was thus concentrated on development of a "low-cost" instrument to measure sky temperature.

4. DETERMINATION OF THE SKY TEMPERATURE

A number of devices exist for the measurement of long-wave radiation such as a pyrgeometer; marketed by Eppley and several models of infra-red radiometers by Barnes. Net radiometers can be used to calculate the quantity.

The principal disadvantage of these instruments is cost. The goal of this project was to develop a device which would be inexpensive, yet could measure the sky temperature with acceptable accuracy.

The device ultimately chosen for construction and testing was designed to be simple and rugged. A thin copper disc with a black top surface has a thermocouple on the bottom to measure its temperature. The disc is insulated from its immediate thermal environment by being kept in an evacuated cylinder. The black surface is exposed to the atmospheric radiation through a window transparent to infra-red wavelengths.

The net heat flux for a body can be expressed as:

$$\dot{Q}'' = \sigma T_S^4 - \sigma \epsilon T^4 + h(T_a - T) \quad (3)$$

If the copper disc is isolated from its immediate thermal environment, we have $h = 0$; then at equilibrium we have

$$T_S = \epsilon^{1/4} T \quad (4)$$

i.e. if the copper plate is coated with a black paint of high emissivity then the temperature of the plate will be approximately equal to the "sky temperature".

5. CONSTRUCTION OF THE DEVICE

The design and materials were chosen so as to minimize the cost of construction. The device is shown in cross section in Figure 1.

The container was drilled out of a solid cylinder of Plexiglas. Both this material and glass are opaque to long-wave radiation; the window was made of a material with high transmissivity in the infra-red. The halide crystals have this property; crystals of KBr and CsI were used.

The vacuum seal was made with a rubber "O" ring, coated with vacuum grease, inserted between the crystal and the cylinder. The crystal was clamped from above with a screw top as this reduced the stresses induced in the crystal by the vacuum.

Two pipes were fitted in the wall at the bottom of the cylinder; one to lead to a pressure guage, the other to lead to a vacuum pump for evacuation of the container.

A thin sheet of Teflon FEP was placed above the screen top. This material has a high transmissivity for long-wave radiation; and was used as a protection for the halide crystal, since these materials suffer degradation upon exposure to moisture.

Figure 1. Device for Measurement of Sky Temperature

Inside the cylinder a cork ring was attached to the wall of the cylinder which supported a styrofoam block. The copper disc rested on the styrofoam block. The cork ring had octagonal sides so as to minimize contact area with the wall. The copper disc was sprayed on the upper surface with a thin coat of Nextel Black Velvet paint. A copper-constantan thermocouple was glued to the bottom of the disc, and the wires were lead to connections in the walls of the cylinder.

6. MEASUREMENTS

The cylinder could be evacuated to a minimum measured pressure of 0.1 Torr. The device was exposed to the night sky; the temperature of the copper disc, and the ambient air temperature were recorded on a Leeds and Northrup Speedomax Thermocouple chart recorder. Simultaneous measurements of the sky temperature were taken with a hand-held Barnes radiometer, the Instatherm model.

Measurements were taken under all weather conditions. A typical set of results is given in Figure 2. For this run of measurements, the sky was cloud-covered for the first part, but cleared to clear sky conditions between 2300 and 2330 hours.

The results recorded with the experimental device cannot readily be scaled to the "sky" temperature. The temperatures of the copper disc show some depression from ambient temperature, but only of a few degrees. There is a marked difference from sky temperature as measured by the Barnes radiometer. The copper disc does respond to changes in the atmospheric radiation; but the depression of the sky temperature below ambient is an order of magnitude greater than that of the copper disc; any calibration that might be attempted would involve very large errors.

Figure 2. Typical Temperatures Measured with the Experimental Device and a Barnes Radiometer

Further sets of measurements are presented in the Appendix. These measurements were taken under a variety of atmospheric conditions; but in all cases the temperature given by the experimental device does not represent sky temperature.

7. DISCUSSION

The principal cause of the poor performance of the device is the failure to eliminate convective heat transfer within the cylinder. As a check, measurements were taken with two of these devices; one was evacuated to an initial pressure of 0.1 Torr, the other was left at atmospheric pressure. The recorded temperatures of the copper plates in the two devices were, within experimental error, the same.

To achieve, and hold, a vacuum with pressure low enough to eliminate the convective heat transfer proved to be extremely difficult; due to the nature of the material used to construct the experimental device. Gases diffuse through Plexiglas at a high rate under low pressure. The minimum measured pressure achievable was 0.1 Torr. When the device was disconnected from the pump during a run of measurements the pressure rose from 0.1 Torr to 0.5 Torr in a period of three hours. In 24 hours the pressure would rise to about 5 Torr.

Another difficulty is that, a significant fraction of the field of view of the copper disc is obstructed by the sides of the container.

8. CONCLUSIONS

The experimental device was not satisfactory for the determination of the "sky temperature".

The type and cost of materials required to maintain the necessary vacuum inside the cylinder, to reduce convection and conduction losses from the copper plate, would be expensive. If further investigations are to be made, it is suggested that they be focused on the determination of the magnitude of the thermal interaction of the device with its immediate environment. Knowledge of the heat transfer coefficient, in Equation (2) would enable a more accurate estimate of the sky temperature to be made.

9. AKNOWLEDGEMENTS

The project was begun in March 1977 with Professor John C. Ward as project leader. The detailed design and construction of the device was done by Tom Francis, a graduate student. The authors of this report became involved in 1979, following Professor Ward's leave of absence in December 1978, and departure of Tom Francis from CSU.

REFERENCES

- [1] Swinbank, W.C. Long-Wave Radiation from Clear Skies. J. Appl. Meteorol., (11), pp. 339-348 (1963).
- [2] Idso, S.B. and Jackson, R.D. Thermal Radiation from the Atmosphere. J. Geophys. Res., (76), pp. 5397-5403 (1969).
- [3] Bliss, R.W. Atmospheric Radiation Near the Surface of the Ground: A Summary for Engineers. Solar Energy, (5), pp. 103-120 (1961).
- [4] Brunt, D. Notes on Radiation in the Atmosphere. Quart. J. Roy. Met. Soc., (58), pp. 389-418 (1932).
- [5] Brutsaert, W. On a Derivable Formula for Long Wave Radiation from Clear Skies. Water Resour. Res., (11), pp. 742-744 (1975).
- [6] LeDrew, E.F. An Estimation of Annual Net Radiation and the Component Fluxes in Southern Canada. Unpublished B.A. Thesis, University of Toronto, 54 p.
- [7] Aase, J.K. and Idso, S.B. A Comparison of Two Formula Types for Calculating Long-Wave Radiation from the Atmosphere. Water Resour. Res., (14), pp. 623-625 (1978).
- [8] Brazel, A.J. and Osborne, R. Observations of Atmospheric Thermal Radiation at Windsor, Ontario, Canada. Arch. Met. Geoph. Biokl., Ser. B, (24), pp. 189-200 (1976).
- [9] Geiger, R. The Climate near the Ground. Second Edition, Chap. 2., Trans. M.N. Stewart et. al., Harvard University Press, Cambridge, Mass. (1959).
- [10] Geiger, R. The Climate Near the Ground. Fourth Edition, Chapter 1. Trans. Scripta Technica, Inc., Harvard University Press, Cambridge, Mass. (1966).
- [11] Ward, J.C. Clear Sky Temperature. Presented at the ISES, U.S. Section, Annual Meeting (1974).

APPENDIX

Weather: Cloudy

Weather: Clear sky

Weather: Cloudy

Weather: Partly Cloudy

Weather: Cloudy,
Slight rain