KAPL-P-000022
(K95088)

CONF-950729--

RECEIVED AUG 20 1998 OSTI

COMBUSTOR DESIGN TOOL FOR A GAS FIRED THERMOPHOTOVOLTAIC ENERGY CONVERTER

K. W. Lindler, M. J. Harper
(Contact: R. Hayes)

July 1995

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

NOTICE

KAPL ATOMIC POWER LABORATORY SCHENECTADY, NEW YORK 12301

Operated for the U. S. Department of Energy
by KAPL, Inc. a Lockheed Martin company

DISCLAIMER

COMBUSTOR DESIGN TOOL FOR A GAS FIRED THERMOPHOTOVOLTAIC ENERGY CONVERTER

Keith W. Lindler
United States Naval Academy
Naval Architecture, Ocean and Marine Engineering Dept
590 Holloway Road
Annapolis, Maryland 21402-5042
Phone: (410) 293-6447 Fax: (410) 293-2219

Mark J. Harper
United States Naval Academy
Naval Architecture, Ocean and Marine Engineering Dept
590 Holloway Road
Annapolis, Maryland 21402-5042
Phone: (410) 293-6452 Fax: (410) 293-2219

ABSTRACT

Recently, there has been a renewed interest in thermophotovoltaic (TPV) energy conversion. A TPV device converts radiant energy from a high temperature incandescent emitter directly into electricity by photovoltaic cells. The current Department of Energy sponsored research involves the design, construction and demonstration of a prototype TPV converter that uses a hydrocarbon fuel (such as natural gas) as the energy source. As the photovoltaic cells are designed to efficiently convert radiant energy at a prescribed wavelength, it is important that the temperature of the emitter be nearly constant over its entire surface. The U. S. Naval Academy has been tasked with the development of a small emitter (with a high emissivity) that can be maintained at 1756 K (2700°F). This paper describes the computer spreadsheet model that was developed as a tool to be used for the design of the high temperature emitter.

NOMENCLATURE

A	area
D	pipe (or hole) diameter
DIV	parameter used to control convergence
f	fluid friction factor
F_{1-2}	radiation shape factor
g	gravitational constant
h	convection heat transfer coefficient
H_L	head loss for fluid flow
k_f	fluid resistance coefficient
k	thermal conductivity
L	pipe length
LHV	fuel lower heating value
m	mass
P	pressure
q	rate of heat transfer
Re	Reynolds number
T	temperature
V	fluid velocity
%	percentage of fuel combusted
Δx	segment length
ϵ	emissivity
η	efficiency
γ	specific weight
ρ	density
σ	Stefan-Boltzmann constant
μ	viscosity

BACKGROUND

A cylindrical design for the TPV converter was chosen for its simplicity and its ability to reduce thermal losses to the ambient. Gaseous fuel from a pressurized tank flows inside a small diameter "flame tube" (see figure 1). A larger diameter tube around the flame tube contains the oxidant flow and serves as the emitter surface. Photovoltaic cells are placed in a cylindrical pattern around the emitter. Numerous holes drilled in the flame tube allow the fuel to flow through to the oxidant. The fuel-oxidant mixture is initially ignited by a spark. Once ignition has been started, combustion is maintained as long

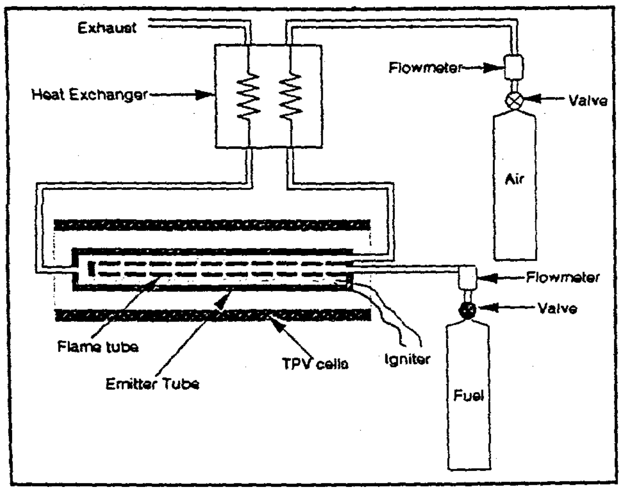

FIGURE 1. SCHEMATIC OF THE TPV COMBUSTOR SYSTEM.

as fuel and oxidant are supplied. Fuel flow is controlled by the number and size of the holes in the flame tube and by a pressure reducing valve located on the fuel tank. Oxidant flow is controlled by a pressure reducing valve on the oxidant tank. In order to improve system efficiency and to maintain the emitter at constant temperature, the hot exhaust gas leaving the combustor can be used to preheat the oxidant.

A computer spreadsheet model of the entire TPV combustor system was written by the authors in order to design a constant temperature emitter. The computer model is used to numerically solve for the temperatures and mass flow rates at all points in the system. In order to solve the necessary energy and mass balances, the flame tube and emitter are numerically broken into 20 segments. The inputs to the program include all dimensions and materials describing the system, fuel and oxidant type, fuel pressure, air/fuel ratio, and heat exchanger effectiveness. The spreadsheet solves for the pressure, temperature, density, viscosity and mass flow rate at each point in the system by simultaneously solving the mass and energy balances for each of the 20 segments. Heat transfer by convection, conduction and radiation are included in the model. Figure 2 shows the mechanisms of heat transfer for each of the 20 fuel, flame tube, combustion gas, emitter and photovoltaic cell segments.

SPREADSHEET DESCRIPTION

The thermophotovoltaic combustor design program was developed using the "Quattro Pro 5.0 for Windows" spreadsheet. Spreadsheets such as this one are organized as a notebook with "pages". Each page consists of a matrix of "cells" arranged in rows and columns. The user can input text, a numerical value or a formula in the cells. The formula in one cell can refer to the values stored in other cells on the same page or another page of the spreadsheet. This gives the user the ability to model extremely complex engineering problems involving equations that are "circular." The combustor design is said to be circular because, for example, temperature affects density which affects mass flow rates which affects the net energy transfer which in turn affects temperature. The circular nature of the problem at hand is actually much more involved than that. Figure 3 is a flowchart representation of the circular nature of the combustor design problem.

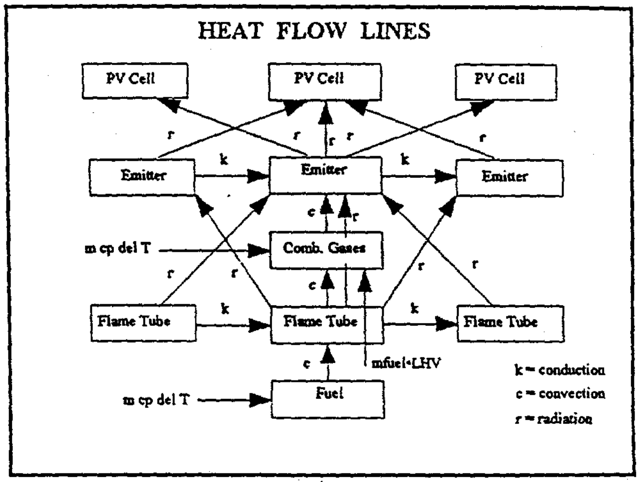

FIGURE 2. FLOWCHART SHOWING THE HEAT TRANSFER MECHANISMS FOR A SINGLE COMBUSTOR NODE.

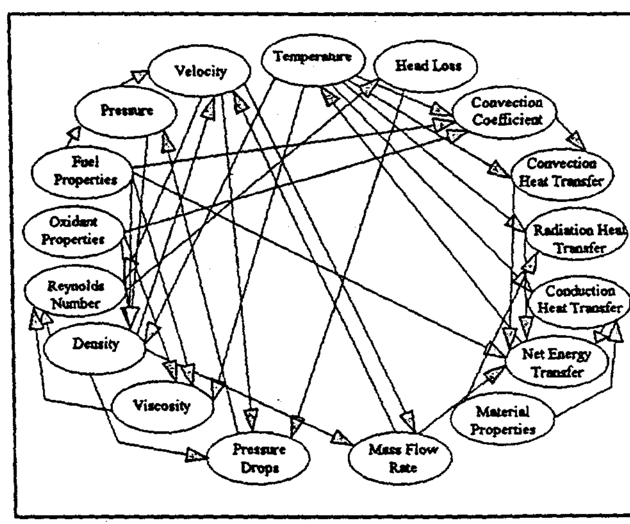

FIGURE 3. FLOWCHART SHOWING THE CIRCULAR NATURE OF THE COMBUSTOR DESIGN PROBLEM.

Each ellipse in figure 3 represents a single page on the spreadsheet. There are several additional pages for data input, graphical output, help screens and a cover page which acts as a table of contents. The table of contents (see figure 4) allows the user to jump to any other page on the spreadsheet through the use of "mouse buttons". In general a first time user would "click" the mouse button labeled HELP and would be led to several pages that described how to use the program. After returning to the table of contents the user would choose "Data Input." A sample data input page appears as figure 5.

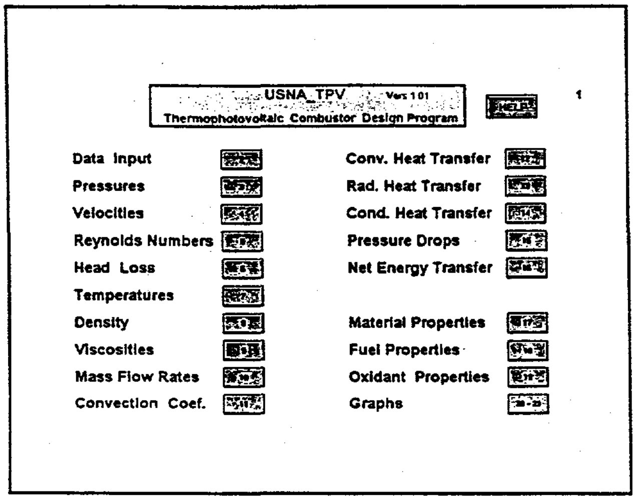

FIGURE 4. THE TABLE OF CONTENTS THAT APPEARS IN THE TPV COMBUSTOR DESIGN PROGRAM.

The numerical values that are shaded in figure 5 indicate the values that the user can specify. All other values are "looked up" or calculated by the spreadsheet. For example, if the user changed the emitter material from Steel to Glass, the values for density, specific heat, thermal conductivity, emissivity and thermal coefficient of linear expansion would be "looked up" by the program, and values that had been previously supplied on the "Material Properties" page would appear on the Data Input page. Also the mass of the emitter segment (remember the emitter is mathematically broken into 20 segments) would be recalculated. In order to see the effect of this material change, the user would press the F9 function key to cause the program to recalculate. In general, the F9 key must be pressed many times due to the circular nature of the problem. After thousands of iterations (each requiring hundreds of calculations), the spreadsheet slowly converges to the new solution.

With patience, the user can change the number and diameter of the holes drilled in each of the 20 segments of the flame tube, the type of fuel and oxidant, the fuel pressure, and the air/fuel ratio, in order to design a combustor that achieves a near constant emitter temperature.

MATHEMATICAL MODEL

While the number of engineering equations used by the TPV spreadsheet are too numerous to list, some of the major equations are given below.

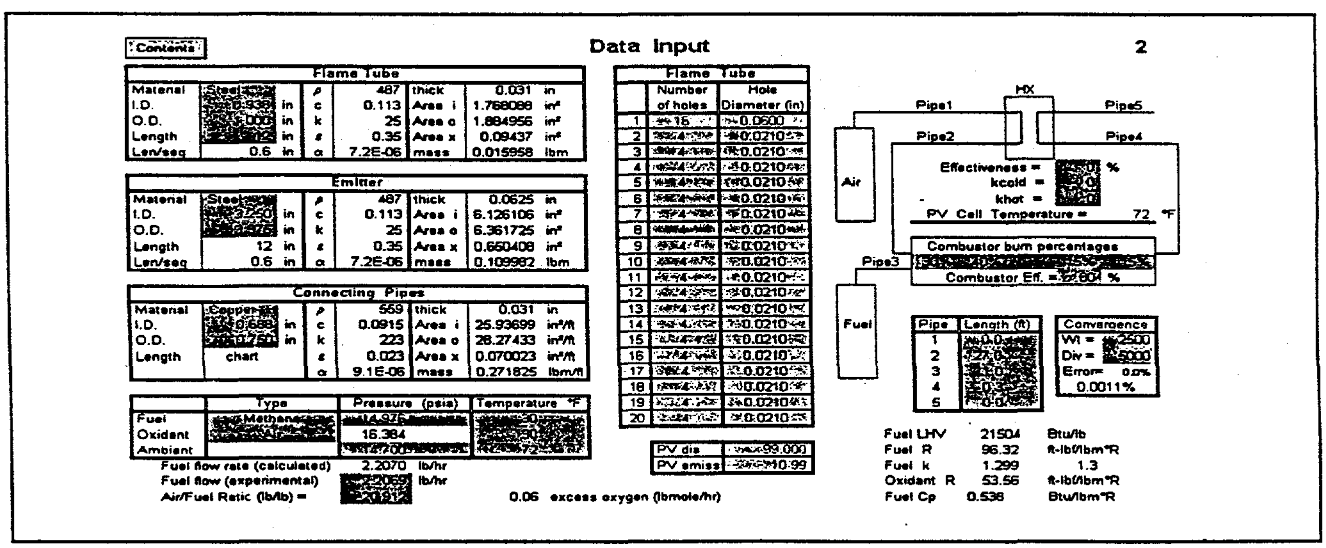

FIGURE 5. DATA INPUT PAGE THAT APPEARS IN THE TPV COMBUSTOR DESIGN PROGRAM.

In order to calculate the mass flow rate of fuel through the holes in the flame tube the head loss equation is solved for the holes in the flame tube in terms of fuel velocity and the pressure drop between the fuel and the oxidant.

$$H_L = (f\frac{L}{D} + \Sigma k_f)\frac{V^2}{2g} = \frac{\Delta P}{\gamma} \tag{1}$$

This equation is then solved for velocity.

$$V = \sqrt{\frac{2g\Delta P}{\gamma(f\frac{L}{D} + \Sigma k_f)}} \tag{2}$$

The value of "k_f" for the entrance and exit to the hole is given as 0.34 and 1.00 respectively (ASHRAE, 1969). For laminar flow, The friction factor "f" is calculated by the well known equation:

$$f = \frac{64}{Re} \tag{3}$$

where Reynolds number is determined by:

$$Re = \frac{\rho V D}{\mu} \tag{4}$$

The above equations again show the circular nature of the problem at hand as the velocity of the fuel indirectly depends on the velocity of the fuel. Once the velocity of the fuel through each of the holes is found, the mass flow rate of the fuel is calculated by:

$$\dot{m} = \rho A V \tag{5}$$

The mass flow rate of the fuel as it flows axially in the fuel tube is calculated by simple conservation of mass. The mass flow through any section of the fuel tube is simply equal to the sum of the flow rates through all of the holes ahead of the section. Similarly the flow rate of combustion gases between the fuel tube and the emitter is calculated by adding the mass flow rate of fuel as it joins the oxidant flow. The spreadsheet also performs a chemical balance in order to separately keep track of the moles of oxygen, nitrogen, carbon dioxide and water vapor flowing between the two tubes. Equation 1 is also used to calculate the axial pressure drop for the fuel and combustion gases flowing in the combustor and in the pipes leading to and from the combustor.

Once the velocities are known, the values of the ~~of the~~ convection heat transfer coefficient are found by equations given by Chapman (1987) for forced convection inside the fuel and emitter tube. Similarly, the convection coefficient for free convection outside the emitter tube is calculated using equations given in Kreith and Bohn (1993). Radiation shape factors between the flame tube segments and the emitter segments and between the emitter segments with the photovoltaic cells are found by an extremely complex equation for shape factors between concentric cylinders found in Siegel and Howell (1972).

Once the convection heat transfer coefficients and radiation shape factors are known, the convection and radiation heat transfer rates can be calculated. The spreadsheet also calculates the heat conducted from any flame tube segment or emitter segment to (or from) the adjacent segments.

$$q_{conv} = hA(T_{wall} - T_{gas}) \tag{6}$$

$$q_{rad} = F_{1\text{-}2}\epsilon\sigma(T_1^4 - T_2^4) \tag{7}$$

$$q_{cond} = -kA\frac{\Delta T}{\Delta x} \tag{8}$$

The heat of combustion of the fuel flowing through the holes of any given segment are assumed to be added to that segment and to the next three segments in the percentages given by the user. These percentages are shown as 30%, 40%, 15% and 15% in the data input page (figure 5).

$$q_{combustion} = \eta_{combustor}\ \%\ \dot{m}_{fuel}\ LHV \tag{9}$$

Next the spreadsheet calculates the net heat into (or out of) each segment of the combustor.

$$q_{net} = \Sigma q_{conv} + \Sigma q_{rad} + \Sigma q_{cond} + q_{combustion} \tag{10}$$

Under steady state conditions, the net heat transfer should be zero. If the spreadsheet determines that the net heat transfer into a node is positive, then the actual node temperature must be higher than the previously calculated value. The new temperature for the next iteration is then simply calculated by:

$$T_{new} = T_{old} + \frac{q_{net}}{DIV} \qquad (11)$$

In the above equation DIV is a user specified parameter. The final solution does not depend on the value of DIV but a large value will lead to slow convergence and a small value can lead to mathematical instability.

SPREADSHEET VALIDATION

Before the spreadsheet could be considered as a design tool, it was necessary to validate that it provides reasonable results. The spreadsheet was used to design a low temperature (approximately 800 F) glass emitter. (Glass was chosen so that the flame characteristics could be observed.) The spreadsheet has the capability of plotting predicted and actual experimental temperatures on the same graph. The results for the glass emitter are shown in figure 6. The spreadsheet provides good results as it only slightly over predicts the temperature on the right half of the emitter. The low temperatures on the left side of the emitter are due to the fact that the heat exchanger was not used for heat recovery, and thus cold air was used for combustion.

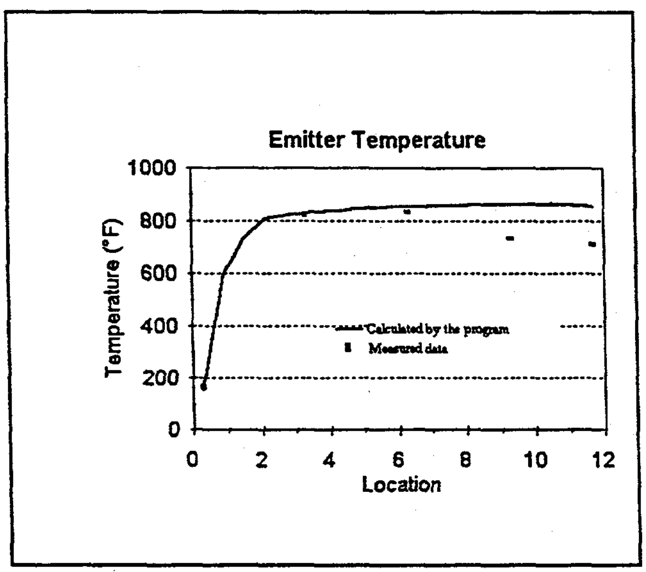

FIGURE 6. EXPERIMENTAL AND CALCULATED EMITTER TEMPERATURE VS. LOCATION FOR THE GLASS EMITTER.

The glass emitter was replaced with a steel tube and the resulting combustor was operated at a slightly higher temperature. The measured and calculated temperatures are shown in figure 7. Again, the spreadsheet does a reasonable job at predicting emitter temperatures. This time the spreadsheet slightly under predicts the temperature on the left half of the emitter and slightly over predicts the temperature on the right half.

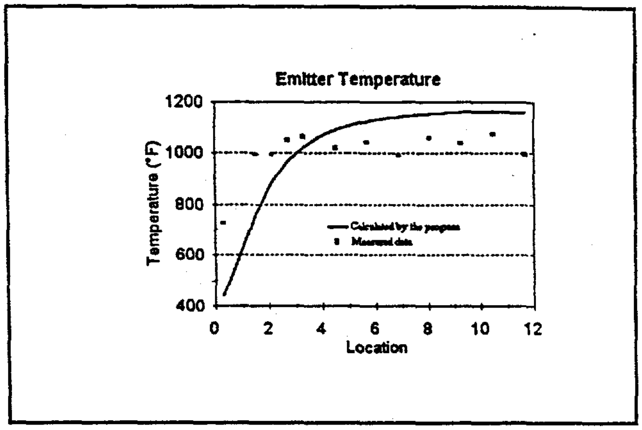

FIGURE 7. EXPERIMENTAL AND CALCULATED EMITTER TEMPERATURE VS. LOCATION FOR THE STEEL EMITTER.

CONCLUSIONS

Computer spreadsheets are very useful for solving complex circular engineering problems. Advantages include the ability to easily organize large numbers of interrelated equations and to graphically present results. The major disadvantage is the time required to converge to a new solution once changes to the data are made.

The spreadsheet developed for the design of a thermophotovoltaic combustor/emitter has been validated using two different emitters at moderate temperatures. The spreadsheet will be used to design a high temperature emitter (1756 K =2700°F) that will maintain a near constant temperature profile. It is expected that the temperature profile will be flatter than achieved in the validation tests, as the hot exhaust gases will be used to preheat the air entering the combustor.

ACKNOWLEDGMENT

This work was sponsored by the Knolls Atomic Power Laboratory operated for the U.S. Department of Energy by the Lockheed Martin Corporation under contract # DE-AC12-76SN00052. Midshipman Robert S. McHenry conducted the combustor experiments.

REFERENCES

ASHRAE, 1969, *ASHRAE Guide and Data Book - Equipment Volume,* American Society of Heating and Air Conditioning Engineers.

Chapman, A. J., 1987, *Fundamentals of Heat Transfer,* Macmillan Publishing Company, New York, NY., pp. 326-327.

Kreith, F., Bohn, M. S., 1993, *Principles of Heat Transfer,* West Publishing Company, St Paul, MN, pp. 327-328.

Siegel, R., Howell, J. R., 1972, *Thermal Radiation Heat Transfer,* McGraw Hill Book Company, New York, NY, pg. 789.