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THE MINTO WHEEL: A CASE STUDY OF COMPUTER MODELING IN UNDERGRADUATE RESEARCH

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ABSTRACT

A problem often encountered in teaching undergraduates is: "How does one stimulate students to extend their interests beyond the narrowly defined boundaries of a textbook and to experience the rewards and frustrations of original research?" We suggest that one answer to this question is to be found in the area of computer modeling of physical systems. An example of the successful application of this technique is the numerical simulation of the Minto Wheel, a solar powered heat engine. We outline here the mathematical model and present simulation results. Simulated thermal efficiency of the bath/wheel/air system is 3%. Student response to special projects of this type is discussed.

INTRODUCTION

What projects are appropriate for undergraduates in a combined Physics-Computer Science curriculum? The computer simulation of a physical system can be both stimulating and educational. In addition, such a project quite often leads to an oral presentation or publication.

This paper discusses student response to the opportunity to do independent study and, in particular, describes one of several student research projects which were undertaken and carried to successful completion in the time span of one academic year. The criteria for success used here include those applied to all research: Does the research increase our knowledge or understanding of nature? Does the research suggest new directions of inquiry? Can the research be construed as "beneficial" in a large social context? And finally we might add: Are the results of interest to the larger scientific community; i.e., are they publishable?

Of nine freshmen through senior level physics and computer science students contacted, seven were interested in pursuing such projects. Of these seven, five presented papers at a collegiate session of the Tennessee Academy of Science (Cates and Fields, 1977; Winchester and Fields, 1977; Guthrie and Fields, 1977; Randall et al., 1977: and Weaver and Fields, 1977). None of these students received extra credit for preparing and presenting his paper.

Several problems, which probably should have been anticipated, were encountered in working with the students. The lack of a formal reward structure—frequent exams and grades—required students either to have or to develop a long-term outlook. This development was reinforced by others in the group who were also anticipating the Tennessee Academy of Sciences meeting where the papers would be presented. Students not "automotivated" either did not choose to begin a project or required frequent encouragement from the instructor. This encouragement sometimes seemed a necessary nuisance to both parties concerned, but was probably well worth the time and effort involved. As is apparnt from the projects mentioned, a wide range of topics was pursued. The suggested topic in each case was chosen after considering the student's special interest or situation, and it is felt that this contributed greatly to the student's ethusiasm.

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THE MINTO WHEEL

One of the more interesting student papers was "A Numerical Model of the Minto Wheel" (Cates and Fields, 1977). The Minto Wheel is a low RPM, high torque engine which can operate between heat reservoirs having a very small temperature differential. For example, the hot reservoir might be at 30° C while the low temperature reservoir might be at 20° C. By a suitable choice of working fluid, the Minto Wheel may be used as a solar powered heat engine operating at "moderate" temperatures.

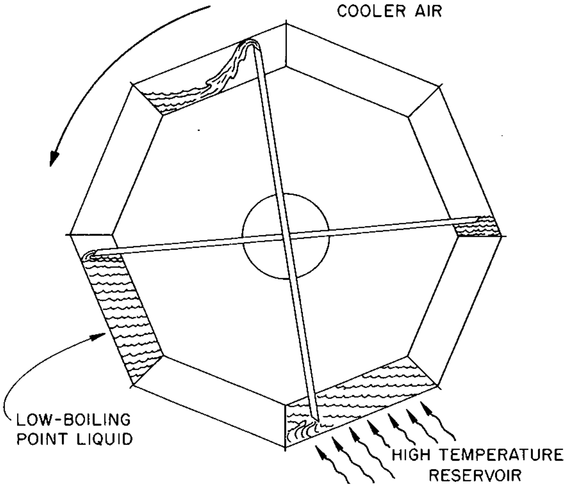

FIG. 1. *Key parts of a Minto Wheel containing four pairs of tanks. its operation is described briefly in the text.*

The Minto Wheel is schematically represented in Fig. 1. Each pair of connected tanks has been evacuated and a low boiling point working fluid such as propane or one of the freons (we assumed Freon-12) has been introduced. The working fluid is vaporized at the temperature of a high temperature reservoir, located at the bottom of the wheel, and the vapor pressure increases causes fluid transfer to the (cooler) upper tank. The torque due to the resulting mass imbalance causes the wheel to turn about a horizontal axis, thus bringing a full tank of cold fluid in contact with the high temperature reservoir. The process repeats itself, producing rotary motion.

COMPUTER SIMULATIONS

The Minto Wheel was the system chosen by one of us (Cates) to model as an undergraduate research project. An IBM 360/50 computer was used. The system had been discussed by Minto (Minto, 1976 a,b) for the situation where constant temperature heat reservoirs were provided; it was our goal to construct a dynamic mathematical model of a physical system encompassing the Minto Wheel, a solar heated water bath of variable size, and the atmosphere. The high temperature reservoir was heated by a time-varying insolation and cooled by evaporation, conduction, and convection, while the upper low temperature reservoir consisted of an atmosphere of diurnally fluctuating temperature. Our simulation spanned a period of one year, with measured solar fluxes and estimated air temperatures correct for an inland location of latitude 37° N. We simulated a sinusoidally varying air temperature with a monthly average T and a superimposed diurnal sinusoidal fluctation T ; i.e.,

$$T_{month} = 12.78 + 13.89 \text{ sine } \pi \text{ (month/6 - } \tfrac{1}{2}) \qquad (1)$$

$$T_{hour} = T_{month} + 8.33 \text{ sine } \pi \text{ ((hour - 6)/12).} \qquad (2)$$

Solar input fluxes to the upper atmosphere were based on measured values (Mazria, 1977) and a 0.59 transmission (Culkowski, 1977) was assumed to simulate cloud cover. Heat losses from the high temperature water bath at the bottom of the wheel were computed explicitly as heat losses through the bath walls by conduction, H_{wall}, and heat losses through the bath surface due to evaporation, H_{evap}, and convection, H_{conv}. These processes are described mathematically by

$$H_{wall} = K_{wall} A_{bath} (T_{bath} - T_{earth})/D_{wall}, \qquad (3)$$

$$H_{evap} = C_{evap}(1\text{-}R)\ (1+K\ \ V)\ (T_{bath} - T_{ref}), \text{ and} \qquad (4)$$

$$H_{conv} = C_{conv}(1\text{-}R)\ (1+K\ \ V)\ (T_{bath} - T_{air}). \qquad (5)$$

In the above equations T represents temperature, A_{bath} the bath wall area, initially chosen 39m², D_{wall} the thickness of mineral fiber wall insulation, chosen 0.15 m, R the relative humidity chosen 50%, and V the wind velocity chosen 2 m/s. Variables denoted by C or K are system constants as is T_{ref}, the parametric reference temperature (10°C) for this equation. Thus, these equations include the effects of relative humidity and windpseed.

The quantity of work done per revolution is simply the mass of working fluid transferred from the lower to the upper part of the wheel per revolution, times the wheel diameter, times the acceleration of gravity. The time per revolution of the wheel was computed by taking the product of the number of tanks on the wheel times the time interval per tank for a quantity of heat, H_{tank}, to be transferred into the tank sufficient both to vaporize the working fluid (1922 calories per tank) and to raise its temperatur to that of the air (typically 1300 calories per tank). This interval, which is the interval for mass transfer from the lower to the upper tank, is simply $H_{tank} /(S_{tank}\ K_{wall}\ T_{grad})$ where S_{tank} is the tank surface area, K_{wall} the wall thermal conductivity, and T_{grad} the average temperature difference across the tank wall divided by the wall thickness. We assume the time average temperature difference across the wall to be $(T_{bath} - T_{air})/4$, since the computer expense to run at various time steps small enough to resolve the heat transfer process, would have been prohibitive. The actual average temperature difference across the wall varies, of course, being the initial bath to air temperature at the start of the time step, and approaching zero well before the end of this time step. Thus the divisor in the preceeding expression is demonstrably greater than 2, and our examination of simulation printout indicated a value of 4 approximated the "correct" value. The power output of the wheel was computed as the work per revolution divided by the time per revolution.

Fig 2 demonstrates one surprising finding of this work. We see that the power output for each hour of the day reaches a *minimum* value at midday. This effect comes about because of the large simulated midday peak in air temperature which causes the temperature differential between the high and low temperature reservoirs to be a minimum at midday. In fact, the water bath is sometimes cooler than the air. The temperature differential reaches a maximum during winter nights.

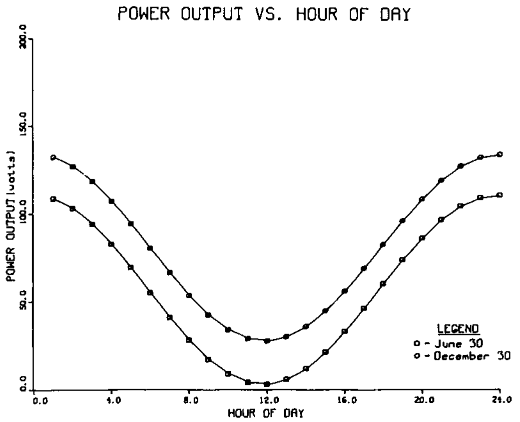

FIG. 2. *Power output vs. hour of the day for representative summer and winter days. At midday, the water bath is colder than the air, producing zero power output. The bath-air interface area is 10m.*[2]

Another interesting finding is shown in Fig. 3, where yearly energy output is plotted against the surface area of the water bath. Note that, for small water bath areas, energy output climbs linearly with increased solar collection area, while for large water bath surface areas, output tends to become independent of area. This result is not so surprising when we realize that, for large water baths, heat extracted by the wheel itself is small in comparison with heat lost due to conduction, convection, and evaporation effects.

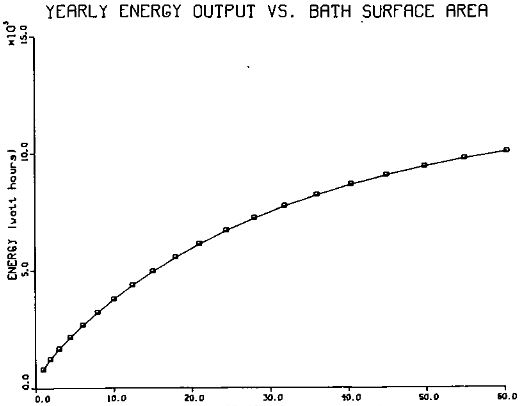

FIG. 3. *Yearly energy output vs. bath-air interface area.*

Although conservative approximations were made at most points in our model formulation, bearing friction was not explicitly accounted for. We also assumed that heat exchange time for one tank (dependent primarily on convection) at the cold reservoir is of the same order or less than at the hot reservoir. Invalidity of the latter assumption in certain cases may explain why one wheel actually constructed failed to deliver the expected power (Mother Earth News, July 1976). Simulation results are obviously dependent on model assumptions just as the operation of a physical device depends on details of its design and construction. A chief advantage of a computer model such as this is that the consequences of alternative assumptions may be seen almost immediately.

The Minto Wheel does not boast a very impressive efficiency although it remains interesting for its economy (Innis, 1976). The maximum theoretically attainable efficiency is itself low, a consequence of the low operating temperature and small temperature differential between the bath and air. The maximum possible efficiency is that of a reversible carnot engine, given by

$$F = (T_{bath} - T_{air})/T_{bath}$$

Such an ideal device, if operated only when the Minto Wheel operates (when $T_{bath} > T_{air}$), would with the same temperature differential have a time-average carnot efficiency of 2.9%. This may be compared to the simulated thermal efficiency of the Minto Wheel system,

$$F = \frac{\text{yearly wheel power output}}{\text{yearly solar input to bath}}, \qquad (7)$$

which in the simulation discussed above was computed to be 3%. A more refined numerical model would predict a lower value after the inclusion of dissipative effects such as bearing friction, fluid turbulence, etc. This value is close to the 2-3% thermal efficiency anticipated for large ocean thermal energy conversion plants (Metz, 1977). The maximum theoretical efficiency of the entire system, consisting of the sun, bath, wheel, and air, is much higher (about 94%) since the high-temperature reservoir is in this case the sun itself.

SUMMARY

In summary, student research projects can be valuable educational activities for both student and intructor. When projects are chosen to mesh with their pre-existing interests, students will respond enthusiastically. The student may discover the value of the iterative process in which examination of model results alternates with refinement of physical concepts. Constructing and testing a computer simulation of a physical system can be an ideal tool for demonstrating physical principles, "teaching" research skills, and showing the necessity of supporting unfounded speculation with quantitative models. It should be noted that deterministic models are only one of a number of valuable computer-related tools for, as one reviewer has pointed out, experience with probabilistic approaches such as Monte Carlo-type simulations can provide an entirely different perspective.

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