HOTCALC Microcomputer Software for Analysis of Commercial Water Heating System Performance

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Abstract

The application, design, and sizing of commercial water heating systems has been hampered by the lack of an accessible tool for evaluating long-term performance and operating energy costs. This lack of resources has limited the application of high-efficiency alternative water heating systems such as heat pump water heaters, refrigeration heat reclaim units or desuperheaters, and waste heat recovery systems. The Electric PowerResearch Institute and the Empire State Electric Energy Research Corporation have developed the HOTCALC microcomputer software to fill that need. HOTCALC uses a three-node stratified tank model and hourly performance simulations for each month to provide performance estimates for five system types: electric storage water heaters, fuel-fired storage water heaters, heat pump water heaters, refrigeration heat reclaim, and waste heat recovery. A detailed recirculation loop model is included. HOTCALC is the first water heating analysis software that addresses the dynamic performance of heat pump water heaters and refrigeration heat reclaim systems, and the first to consider interactions between space cooling loads and heat pump water heater operation. Unlike other common models, it uses hourly inputs rather than longer-term average load and operations figures. Outputs include energy consumption, estimated demand, efficiency, and utility cost for all water heating system components. For heat pump water heaters, estimates of beneficial cooling output and value are provided.

HOTCALC is designed for easy use and includes features for comparison of results from multiple runs, results and system design diagnostics, and a detailed context-sensitive help system with page references to ESEERCO's and EPRI's companion 310-page **Commercial Water Heating Applications Handbook,** *EPRI TR-100212. HOTCALC provides reliable performance estimates and removes much of the uncertainty in system selection and design, thus facilitating the use of more efficient and effective commercial water heating systems. Reactions from users have been positive and comparisions to measured performance data have been very favorable.*

Introduction

The application, design, and sizing of commercial water heating systems has been hampered by the lack of an accessible tool for evaluating performance and operating energy costs. Traditional design methods focus almost entirely on sizing storage water heating systems to ensure an adequate hot water supply. With the exception of solar water heating systems, little attention has been paid to methods for prediction of performance and operating costs or to trade-off decisions and design optimization. Without a reliable performance evaluation tool to evaluate the likely future savings, it is difficult to justify the higher initial cost of these systems. This lack of resources has limited the application of enhanced-efficiency alternative water heating systems such as heat pump water heaters, refrigeration heat reclaim units or desuperheaters, and waste heat recovery systems.

Equipment manufacturers and others have responded with simple manual calculation procedures and spreadsheet models that can provide misleading results. Such methods rely on constant equipment performance parameters and average daily or monthly loads. While such an evalaution approach yields acceptable results for conventional water electric resistance and fuel-fired heaters, it is not reliable for enhanced-efficiency systems. Simple methods also do not consider run time limitations imposed on heat pump water heaters by space cooling loads or limitations on refrigeration and waste heat reclaim systems imposed by the dynamic aspects of the availability of the heat source.

In response to this need, the Electric Power Research Institute and the Empire State Electric Energy Research Corporation developed the HOTCALC microcomputer software. HOTCALC provides performance analyses of the five common water heating system types:

- Electric storage water heaters
- Fuel-fired storage water heaters
- Heat pump water heaters (HPWH)
- Refrigeration heat reclaim systems (RHR)
- Waste heat recovery systems (WHR)

Using HOTCALC, a user can describe a specific water heating application and then quickly assess the performance of alternative system designs. HOTCALC is particularly useful for comparing enhanced-efficiency alternatives to conventional water heating systems. A comparison feature allows direct review of summary results from two runs on a single screen. HOTCALC's diagnostic features make suggestions for fine-tuning system designs. For heat pump water heaters, HOTCALC examines the complex interactions between water heating and space cooling loads and the dynamic influences on unit performance.

HOTCALC has been successfully used for its intended purpose of applications and design decision making. In addition, it has shown value for utility program planning and as an education tool, allowing users unfamiliar with water heating technologies to obtain a sound understanding of system characteristics and influences on performance.

HOTCALC was recently revised to version 2.0, incorporating new features requested by users.

Background

HOTCALC was created for use by a diverse group of technically-oriented design professionals and utility marketing representatives. Consequently, HOTCALC is structured to allow use at both simple and detailed levels, recognizing the varying needs and capabilities of users. Primary development objectives were ease of use and provision of relevant technical and economic information for real-world decision making. The second objective required the inclusion of dynamic equipment performance models, consideration of loads and constraints on a hourly basis rather than reliance on longer-term averages, and examination of interactions between various loads and equipment.

The inputs and outputs can be addressed either on a simpler level to obtain basic information or on a highly detailed level to address specific issues. Simplicity in input is enhanced by the provision of sound default values and input data checking. All output reports consist of a summary of key figures followed by detailed listings of other results and determinants.

A major influence on the structure of HOTCALC was the extreme uncertainty and variability in water heating loads in commercial buildings. Volumetric hot water usage is seldom known in quantitative terms except as speculation and guesses. In addition, hot water usage varies greatly at a particular facility with factors which cannot be readily described. The level of precision in the simulation calculations must be balanced against the uncertainty in the fundamental water heating load.

HOTCALC Inputs

The functional inputs to HOTCALC are grouped into two categories: load descriptions and system descriptions. Inputs to HOTCALC were restricted to information which typical users can obtain easily. Key water heating load determinants include the volume of hot water used, the desired supply temperature, and climatic information. Hourly usage may be scheduled by specifying an average daily total hot water usage figure and then selecting from one of 14 standard hourly load profiles for various facility types. Users may create custom profiles for input information. If desired, volumetric load may be varied on a monthly basis. Weather data files supplied for 75 U.S. locations include typical supply water temperatures as well as dry-bulb and dewpoint temperature and diurnal temperature variation for use in heat pump water heater simulations. A recirculation loop may be described in terms of pipe dimensions and insulation characteristics. The user describes the water heating system using standard information available from manufacturers' catalogs, or in the case of conventional systems, from rating institutions. The performance simulation methodology was shaped by the lack of heat pump water heating test data and performance rating standards and the almost total lack of reliable performance information. To avoid imposing unreasonable requirements for input data on users, it was necessary to develop characteristic performance relations for the heat pump water heaters in general and modify them during simulations with readily-available information on the specific model being examined. Refrigeration heat reclaim systems were modeled using a calculation methodology developed previously by EPRI. Conventional water heating systems can be conveniently modeled using readily-available standard performance rating criteria and simple calculations.

HOTCALC Outputs

Following simulation calculations, HOTCALC provides a listing of all relevant thermal, energy, and cost figures for the water heating load and system performance. Both annual aggregate and monthly figures are provided. Results are available in tabular or graphical formats on screen, as printed copy, and as ASCII disk files. A link file containing electric and gas water heating energy input and heat pump water heating cooling output may be written to disk for subsequent use in EPRI's COMTECH 3.0 software. COMTECH is a technology screening tool which considers all the component loads for a facility and evaluates operating costs using a detailed and flexible utility rate structure model. The link capability is useful for consideration of the water heating load information in the context of the entire facility.

Simulation Methodology

General Procedures

HOTCALC relies on a three-node stratified tank model with iterative solutions using a user-selected time step to develop hourly performance figures. Calculations are performed for each of two typical days of each month; the two day types are used to represent differences in operations, such as weekdays and weekends. Figure 1 provides a generalized schematic of the simulation.

In contrast to simpler performance calculation procedures, HOTCALC considers several factors that significantly affect the performance of enhanced-efficiency water heating systems. Consideration of the following factors permits reliable estimates of performance for enhanced-efficiency systems and also provides marginal improvements in the quality of estimates for conventional systems.

- **Dynamic equipment performance.** The output and efficiency of conventional systems is nearly constant over a wide range of conditions and can be adequately described with constant figures. However, enhanced efficiency systems show major differences in performance under normal ranges of conditions. For instance, the output and efficiency of a heat pump water heater vary 25 to 50% with typical variations in inlet water temperature and evaporator air wet-bulb temperature.
- **Dynamic loads.** Simpler calculation methods rely on daily or monthly averages of water heating load and other constraints. Greater reliance on storage capacity and reduced reliance on heating capacity (typical of enhanced-efficiency systems and conventional systems operated in off-peak modes) creates a need to consider operations on a shorter term to avoid overstating the output of the primary system and understating the higher-cost output of the supplemental water heating system.
- **Equipment interactions.** Simple calculation methods assume that the water heating system can operate whenever a water heating load exists. In reality, the availability of the heat source as determined by normal cycling and the load/capacity balance limit the operation of refrigeration and waste heat recovery systems. Similarly, the operation of heat pump water heaters with controls or operators that respond to space temperature is governed by space cooling loads and conditions.

Both stand-alone and preheat system configurations are accommodated, with energy inputs into the storage tanks from separate heat pump water heaters, refrigeration heat reclaim systems, or waste heat reclaim systems or from integral conventional electric resistance elements or gas burners. Heat loss from tanks, connecting piping, and a recirculation loop is addressed. The cooling effect of a heat pump water heater may be ignored or tracked if it is assumed to have value. Various control schemes may be imposed on the systems. The simulation process successfully handles configurations and geometries typical of small- and medium-capacity commercial water heating systems.

Simulation calculations are conducted on either two-, six-, or 15- minute time steps. The longer time step was intended to allow faster solutions for preliminary simulation runs during a user session with the shorter time step to be used for final results. Experience has shown little difference in the results for 2- and 15-minute steps and users typically rely almost exclusively on the 15-minute setting. An iterative solution is used to solve for load, energy, performance, and efficiency figures.

Results from each time step are aggregated to hourly values and stored in a 24-hour simulation for each of the two day types. Results are extrapolated to monthly and annual values using the user-specified number of primary and secondary days for each month.

Multiple water heating devices of equal size and type may be used in either series or parallel piping arrangement. Enhanced-efficiency water heating systems (heat pump water heaters, refrigeration heat reclaim, and waste heat reclaim) may incorporate either electric resistance or gas supplemental water heating systems.

Stratified Tank Model

Water tanks are modeled as vertical cylinders divided into three equal-volume zones. Each zone is assumed to be fully-mixed and is represented as a single isothermal node. Figure 2 provides a schematic of the tank model for a system with remote heat input from an enhanced-efficiency device.

The structure of the model was chosen to reflect typical equipment designs. Individually-controlled electric energy inputs are accommodated in each node; gas energy inputs are allowed only in the bottom node. Supply water flow is routed from the bottom node upward through the middle node and exits from the top node. Recirculation loop flow is from the top node with a return to the bottom node. HPWHs, refrigeration heat reclaim systems, and waste heat

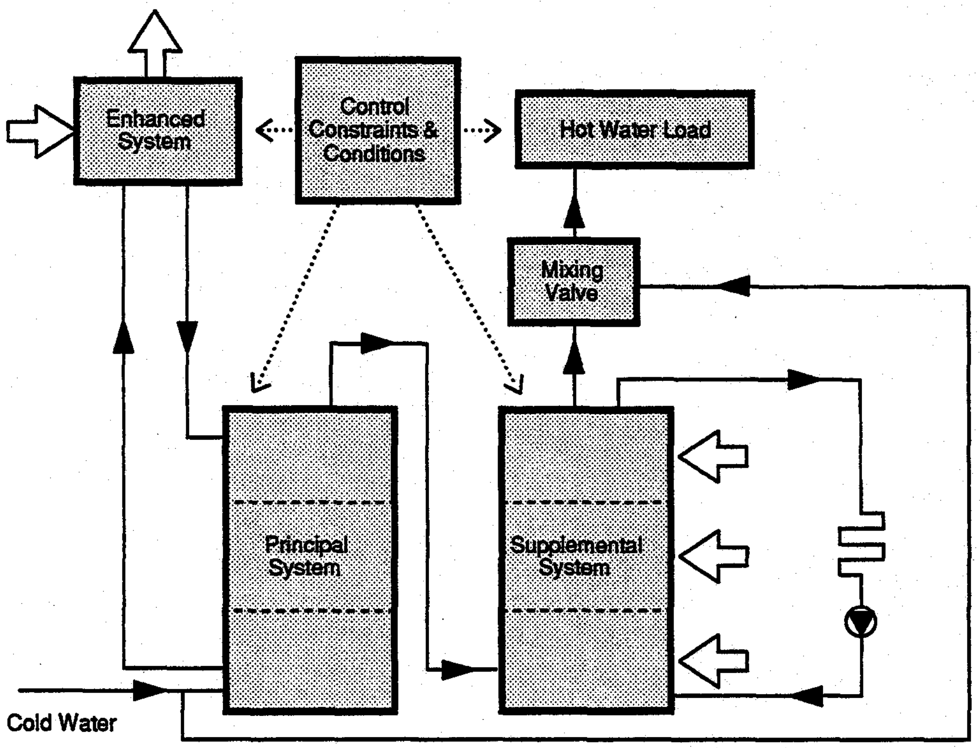

Figure 1. Simulation Model

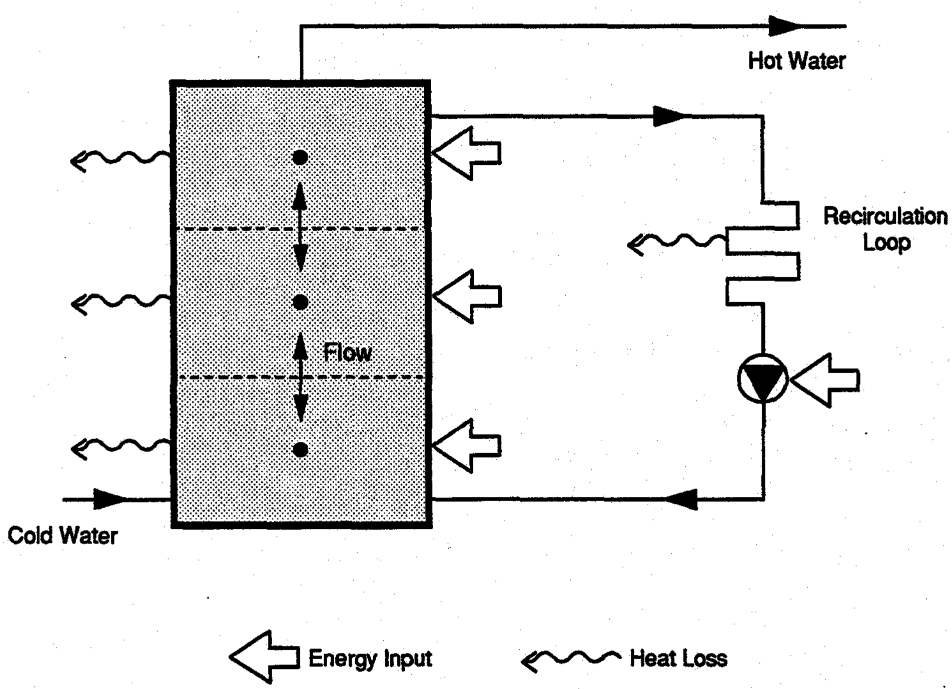

Figure 2. Stratified Tank Model

reclaim systems supply energy to the tank through separate piping loops which draw water from the bottom node and return heated water to the upper node. Stand-alone systems are modeled with the return to the middle node. Additional constraints on system geometry are imposed to represent normal practice and to reflect proper function.

The tank model is simplified to achieve short simulation times. However, given the uncertainty in water heating load information, there is no significant compromise in the reliability of the results. The following simplifying assumptions are made.

- Standby loss is calculated from a standard rating term describing overall rate of heat loss (fraction of stored heat lost per hour) adjusted for the surface area of each node. This avoids tedious geometric and thermal property descriptions.
- Heat transfer occurs vertically between nodes by convection and mass transfer; conduction is ignored.
- Adjacent nodes are mixed fully if the temperature of the lower node exceeds that of the one above.

Mass and energy balances are performed for each node during the time step and iterative solutions for tank node temperatures are obtained. Calculations are looped until close agreement is achieved in beginning and ending tank temperatures. Ignoring the discontinuities in load and conditions from month-to-month in this manner shows little effect on annual results. Energy flows are summed to obtain loads, component energy use and electric demand, heating device output, efficiency, run time, piping loss, standby load, and recirculation loop load.

Water Heating Loads

Hourly water heating load is calculated for each day type from hourly volumetric hot water usage, hourly hot water delivery temperature, and a monthly value of cold water supply temperature. Volumetric load may be varied from month to month.

Standby heat loss is calculated for each tank node using the node temperature at each time step, node volume, area-weighted standby loss rate, and monthly values of ambient temperature. Heat loss from the recirculation loop and the piping between enhanced-efficiency systems and their associated storage tanks is calculated similarly, using a physical description of the piping and flow rate. Electric energy consumption by the pump is tracked as the product of the rated Wattage and the run time.

Electric Demand

For an hour of the day specified by the user, estimates of coincident electric demand are obtained from the hourly values of the electrical input to each water heating and air conditioning system component. The user can review and edit demand estimates prior to the execution of cost calculations.

Energy and Demand Cost

Energy and electric demand cost calculations are performed using monthly incremental utility costs for gas and electric energy and electric demand. Fixed monthly costs may also be specified to reflect other costs such as maintenance and insurance.

Efficiency

Overall efficiency figures are calculated for each water heating device and for the system as a whole using gross inputs and useful output values from the simulation.

System-Specific Considerations

Heat Pump Water Heaters

While the performance of conventional electric resistance and gas storage water heaters is relatively independent of conditions, heat pump water heaters are strongly affected by water temperature and conditions at the evaporator. Unfortunately, detailed performance maps or relationships for commercial units have not been developed and the limited information in existence is not generally available. This problem was addressed by applying capacity and efficiency information specific to individual HPWH models to generalized performance relationships.

Using proprietary performance data supplied by manufacturers, second-order equations were developed to represent heat pump water heater energy consumption, cooling thermal output, and water heating thermal output as functions of entering condenser water temperature and entering evaporator wet-bulb temperature. These relationships are modified by readily-available single-point performance information for the specific unit being studied. For HPWHs with cooling-only capability, similar equations are used to predict thermal output and energy input in the dedicated cooling mode as functions of exterior ambient dry-bulb temperature and entering evaporator wet-bulb temperature.

Supplemental air-conditioning system energy consumption is calculated using standard energy efficiency ratio (EER) values and part-load efficiency profiles entered by the user. The value of cooling produced by the HPWH operating in the normal water heating/cooling and cooling-only modes is calculated using the supplemental air-conditioning system's rated EER modified with a part-load efficiency equation.

HPWH Cooling Performance

The space cooling load which the HPWH helps offset is calculated from information readily available from the air conditioning load calculation for sizing equipment. The space cooling load is modeled as the sum of an internal load and the product of an overall coefficient of heat transfer and the hourly indoor/outdoor temperature difference. The internal load is calculated as the product of an internal cooling load at design conditions and a set of user-specified hourly modifiers. The overall heat transfer coefficient represents the "skin" or external portion of the cooling load which varies with the temperature difference across the building envelope; it is developed from the design cooling load and the design temperature difference. The indoor/outdoor temperature difference is found for each hour using a specified interior temperature and an outdoor temperature calculated by applying a sine function representing daily temperature variation to a monthly average outdoor air temperature and a monthly average diurnal temperature variation. The user can introduce the effect of other factors governing the cooling load through the use of separate hourly cooling load modifiers for internal and external loads.

Refrigeration Heat Reclaim Systems

Refrigeration heat reclaim systems capture heat normally rejected by the condenser of a vapor compression refrigeration device and apply it to a useful purpose. Hourly RHR heat source availability is modeled with capacity and efficiency figures for the compressor at design conditions, a user-specified part-load relationship, and a set of hourly and monthly capacity/run time modifiers. The heat source value for a particular hour is the product of the thermal output capacity at design conditions, the hourly fraction, the monthly fraction, and a part-load factor.

Both the typical desuperheating mode of operation and full-condensing operation are addressed. It is assumed that the heat exchanger has adequate capacity for the selected operating mode: either desuperheating or full condensing. For full condensing, the quantity of heat rejected to the condenser each hour is calculated as the compressor cooling output plus the compressor energy input. The circulating pump run time is modulated to limit heat exchanger leaving water temperature to 180° F, to match typical practice.

For desuperheating systems, the amount of heat available for recovery is calculated using a relationship between superheat and cooling load as a function of condenser discharge temperature and compressor efficiency published in EPRI's *Assessment of Restaurant Heat Recovery and Load Leveling*, Volume 3, EM-4461P, March 1986. Relationships are provided for three common refrigerants at four evaporator temperatures representing typical conditions.

Waste Heat Recovery Systems

HOTCALC incorporates a general waste heat recovery model for simulating the performance of heat recovery equipment acting on any fluid stream. The heat exchanger is described with a heat exchange effectiveness figure and fluid flow rate on the potable water side. The availability of heat for recovery is modeled with inputs for the temperature and heat capacity of the source at design conditions and a set of hourly and monthly modifiers. The fluid stream is assumed to be isothermal.

Useful heat output is the product of heat exchanger effectiveness, heat capacity, and temperature difference between the storage tank and source temperature. The heat input to the tank is regulated by a thermostat sensing the temperature in the lower node. A 180° F upper limit is imposed.

Execution Time

Execution times for HOTCALC simulations vary significantly with the complexity of the system being simulated. Complete simulations for simple systems using the coarsest time step are completed in less than 10 seconds on computers using 33 mHz 486 processors and require approximately two minutes on a 386-20 computer without a math coprocessor. The most complex systems using multiple heat pump water heaters in series, two day types, and the two minute time step require about nine minutes on the 486-33 and 140 minutes on the 386-20. Results with the 15-minute time step compare closely with those obtained with the two-minute time step and most actual systems simulated are less complex than the complex example used for these timings. In typical use, execution times of two to three minutes or less are encountered on faster computers.

User-Oriented Features

HOTCALC incorporates several user-oriented input and output features, including default values for all inputs and error checking of inputs. A diagnostics feature offers suggestions for fine-tuning the water heating system design, and a comparison feature allows the user to examine differences between two simulation runs. A context-sensitive, on-line help system provides text descriptions of all input and output features and program operating instructions. In addition, page references to a companion 310-page *Commercial Water Heating Applications Handbook*, EPRI TR-100212, December 1992, provides the user with details on commercial water heating technologies, applications, and design.

Comparison to Measured Results

The following results were reported from users of HOTCALC.

Commercial Laundry, Ontario, Canada

A two-stage heat recovery system recovers energy from dryer exhaust to pre-heat water to an electric resistance water heater. Daily hot water usage application, design, and sizing of efficiency improvements and alternative high-efficiency commercial water heating systems. Unlike previous calculation methods, it addresses factors that significantly affect the performance of enhanced-efficiency water heating systems. HOTCALC balances complexity and calculational rigor with the needs and input information resources of the user.

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