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Original Research Article

Sizing of thermal energy storage devices for micro-cogeneration systems for the supply of domestic hot water

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ABSTRACT

Cogeneration technologies are increasingly being utilised in the construction sector. Micro-cogeneration technologies only become economically feasible after they have been in operation over a lengthy period of time and this makes necessary the sizing of appropriate storage systems. The integration of cogeneration within overall heating and cooling loads requires the use of complicated simulation codes. However the need for this integration can be removed with the design of a cogeneration system which only covers the thermal demand required for the provision of domestic hot water, this demand being relatively easy to forecast. Based on a given domestic hot water demand, a calculation procedure for sizing the storage system is presented. This procedure is experimentally validated with only minor differences between expected and actual results, this being attributable to the limitations of the experimental set-up. It achieves more than acceptable results when compared with other model designed for heating applications in the building sector.

Introduction

Cogeneration, also known as combined heat and power (CHP), is a highly efficient method of utilising fossil resources and its use has therefore become increasingly widespread in the construction sector in the search for primary energy savings, reductions in electricity transport losses and security of supply [1,2]. Combined with renewable resources, it has also been demonstrated to be a rational way of cutting building CO_2 emissions [3]. From a technological point of view, cogeneration is available in a number of modalities: reciprocating internal combustion engines, micro-turbines, fuel cells, and reciprocating external combustion engines based on Stirling cycle [4,5].

The building sector differs from the industrial sector due to the variable profile of the demand. It is thus necessary to make an appropriate choice in terms of the size of engines and operating strategy [6–8]. In order to achieve the optimal operation of the system, an energy storage system is required [9]. There are a variety of options, including stratified hot water [8,10] phase change materials [11] and the use of the ground as a heat reservoir [3,12].

The variability of demand referred to above necessitates the use of computational codes in the design phase in order to analyze the coupling between the storage system, the demand and the engine [6,10,13–15]. It is even necessary to define procedures for creating demand profiles and selecting representative climate loads [16,17]. In the operation phase the performance of the system has to be monitored in order to correct deviations and achieve selected goals [10,18,19].

Experience in the modelling of the storage system, which involves the use of numerical methods to solve the dynamic of the problem, comes from the production of thermal solar energy [20,21]. With regard to cogeneration systems, the accurate modelling of the storage system has been demonstrated to be a key factor in the performance of the plant, in both technical [22] and economic terms [5,23].

This paper presents a special method of integrating cogeneration into a building, which is the supply of domestic hot water (DHW). The demand profile for domestic hot water, although an hourly variable, is easily forecasted, and is therefore possible to formulate an analytical procedure for the sizing of the thermal storage system. Avoiding sophisticated numerical procedures entails the deployment of cogeneration in the supply of domestic hot water, permitting an increased use of this technology in the building sector. Today, charts and diagrams exist for the sizing of suitable thermal storage systems [25], the importance of the accurate sizing of the thermal energy storage system for the profitability of micro-cogeneration systems for residential building applications having been demonstrated [5]. This paper presents a systematic calculation procedure which includes a simple equation for the integration of cogeneration in domestic hot water systems. This procedure has been validated in an experimental set-up which reproduces the demand in 100 flats and has been compared with other method proposed in the literature [25].

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Nomenclature

Greek symbols

ε_n	decision variable [–]
ρ_w	water density [kg/dm^3]

Latin symbols

BUE_n	back-up energy at n period [kWh]
C_d	DHW consumption volume in a day [dm^3]
C_{du}	DHW unitary consumption volume in a day [dm^3/person]
C_n	DHW consumption flow rate at n-period [dm^3/h]
C_w	water specific heat [kWh/kg K]
CHP	combined heat and power
DHW	domestic hot water
H_{bu}	thermal power supplied by the back-up system to the demand [kW]
H_c	thermal power to supply domestic hot water [kW]
H_d	thermal power delivered by cogeneration system to demand [kW]
H_e	thermal power released by the engine at the heat exchanger [kW]
N_f	number of flats [–]
N_p	number of persons per flat [–]
Q_c	volume flow rate of domestic hot water [dm^3/h]
Q_e	volume flow rate through the heat exchanger in the experimental set-up [dm^3/h]
SE	actual stored energy in the tank of the experimental set-up [kWh]
SE_{max}	maximum amount of storable energy [kWh]
SE_{n-1}	stored energy at $n-1$ period [kWh]
SE_n	stored energy at n period [kWh]
T_d	achieved DHW use temperature with the experimental system [°C]
T_i	net water temperature [°C]
T_k	measured temperature at position k in one tank [°C]
t_n	n period long [h]
T_p	DHW supply temperature [°C]
T_u	DHW use temperature [°C]
V	volume of the storage device [dm^3]
WE_n	waste energy at n period [kWh]

Methodology

System description

The cogeneration system modelled in this paper is designed to be integrated within the DHW supply system of a centralized plant. The demand is therefore that of a certain number of flats (typically more than 80) whose DHW is supplied by a thermal plant. The cogeneration engine is designed to cover the minimum demand, that is, when the temperature of the net water is at its peak. A complementary thermal system is therefore necessary to support the cogeneration engine in covering the demand at other times. This system is sized for the continuous operation of the engine without any dissipation of waste energy. Consequently, thermal power from engine is given by Eq. (1).

$$H_e \cdot 24 = C_d \cdot \rho_w \cdot C_w \cdot (T_u - T_i) \tag{1}$$

Thermal storage is achieved with the stratification of hot water in the tank. Therefore when the overall volume of the tank is divided into various sub-tanks, each one is connected to the rest in a serial arrangement which achieves an appropriate variation of temperatures. The relation between the maximum amount of storable energy and the volume of the tank depends on the thermocline in the tank. Former regulations in Spain [24] recommend the relation given in Eq. (2). Assuming 60 °C for both the inlet (Tp) and outlet (Tu) temperatures of the storage system and a net water temperature (Ti) of 16 °C, a conversion factor of 30.73 kWh/m^3 is obtained. Fig. 1 shows a general layout of the system.

$$SE_{\max} = \rho_w \cdot C_w \cdot V \cdot (T_p - 0.4 \cdot T_u - 0.6 \cdot T_i) \tag{2}$$

Sizing of the energy storage

Energy storage is necessary because DHW demand does not present a constant profile over time. Consequently the first step is to define a demand profile for DHW. In Spain the Technical Building Code [23] does not define this profile but only the water consumption per person per day. A continuous consumption has been assumed between 5 a.m. and 11 p.m., with three peaks overlaid over this continuous consumption, one of 2 h at 7 a.m., and two of 1 h at 3 p.m. and 9 p.m. Fig. 2 shows the resulting profile. Other profiles are possible and numerical results will vary accordingly. However, the calculation procedure will still be valid.

The ratio of peak to minimum consumption depends on the number of users (flats): the higher the number of users, the lower this ratio. Again, Spanish regulations do not impose any ratio, so a reasonable relation has been assumed (Fig. 3), based again on former Spanish regulations [24]. For a given number of flats, Fig. 3 determines the peak to minimum consumption ratio and by integrating the profile given in Fig. 2 we can calculate the consumption (flow rate) for peak and minimum demand periods, when consumption in a day is assumed to be 22 L at 60 °C per person in a three-person per flat [23].

The calculation procedure for the system includes two phases: the sizing of the storage device and the calculation of the possible amount of waste energy and energy supplied by the back-up system (back-up energy).

The sizing phase begins with the calculation of the thermal power taken from the engine, which has to be able to cover the energy demand required to supply the consumption of DHW in a day. In order to avoid the dissipation of thermal energy from the engine, this calculation is made for maximum net water temperature, this information normally being available for periods of one month. Consequently, except for during the design month, the back-up system is always supplying an amount of energy to complete the thermal demand resulting from the supply of DHW.

Sizing calculation is an iterative procedure and an initial size ($SE_{\max}$) is therefore assumed. The procedure begins with the application of the energy balance given in Eq. (3) to each period (peak, minimum demand or zero consumption). The application of Eq. (3) produces a value of ε_n which, according to Table 1, determines the quantity of waste energy, back-up energy and stored energy at the end of the n-period, all of which will be used in the balance in the next period.

$$SE_{n-1} + H_e \cdot t_n = C_n \cdot t_n \cdot \rho_w \cdot C_w \cdot (T_u - T_i) + \varepsilon_n \cdot SE_{\max} \tag{3}$$

Once Eq. (3) has been applied to a complete day, the overall quantity of waste energy and back-up energy can be calculated. The