Sizing of thermal energy storage devices for micro-cogeneration systems for domestic hot water preparation. Theory and experimental results

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Abstract

Cogeneration technologies are entering in the building sector at a fast pace. Micro-cogeneration technologies require long time of operation to achieve the economic feasibility so it is necessary to size adequate storage systems. Integration of cogeneration with the overall heating and cooling loads requires the use of complicated simulation codes. Instead of this integration it is possible to design the cogeneration system only to cover the thermal demand required to prepare the domestic hot water, whose forecast is easier. Based on a given domestic hot water demand a calculation procedure for sizing the storage system is presented. This procedure is experimentally validated finding low discrepancies which have been explained by the experimental facility limitations.

Keywords

Cogeneration, domestic hot water, stratified hot water storage system.

Introduction

Cogeneration is spreading in the building sector in order to achieve primary energy savings, electricity transport losses reduction and security in supply, being a highly efficient procedure to use fossil resources [1]. Cogeneration combined with renewable resources has revealed as a rational way for curbing building CO2 emissions [2]. From the technological point of view there are a lot of options as reciprocating internal combustion engines, micro-turbines, fuel cells and reciprocating external combustions engines based on Stirling cycle [3].

The building sector differs from the industrial one in the variable profile of the demand. So, it is necessary to make an adequate selection of the size of the engines and the strategy of operation [4-6]. In order to achieve the optimal operation of the system it is necessary to include an energy storage system [7]. There are different options, from stratified hot water [6,8] to phase change materials [9] and the use of the ground as a heat reservoir [2,10].

Variability of demand imposes the use of computational codes in the design phase in order to analyze the coupling between the storage system, the demand and the engine [4,8,11,12,13]. Even it is necessary to define procedures to create demand profiles and select representative climate loads [14,15]. In the operation phase it is necessary to monitor the performance of the system to correct deviations and to achieve the selected goals [8,16,17].

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This paper deals with a special way to integrate the cogeneration in the building, which is trough the domestic hot water (DHW) preparation. Spanish Building Code [18] obliges to use thermal solar energy to prepare domestic hot water in new residential buildings. As an alternative to solar energy it admits cogeneration, which has certain advantages over solar energy like lower space requirements, lower investments and a lower payback period due to the Spanish feed in tariff system applied to the electricity produced with cogeneration [19].

The domestic hot water demand profile, although hourly variable, is easily forecasted so, it is possible to avoid the use of complicated simulation codes to design the system. The only sensitive evaluation is the sizing of the storage volume. This paper gives a systematic calculation procedure which entails to a simple equation. This procedure has been validated in an experimental facility which reproduces a demand of 100 flats.

Methodology

System description

The cogeneration system is designed to be integrated with the DHW preparation system of a centralized plant. So, the demand is constituted by a certain number of flats (typically higher than 80) whose DHW is prepared in a thermal plant. The cogeneration engine is designed to cover the minimum demand, that is, when water supply temperature is the highest. So, a complementary thermal system is necessary to support the cogeneration engine for covering the demand in months other than the design one. The system is sized for the continuous operation of the engine and no waste energy dissipation. So, thermal power from engine is given from 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. So, when the overall volume of the tank is split in various sub tanks each one is connected to others in a serial arrangement achieving a suitable variation of temperature. Relation between the maximum storable energy and the volume of the tank depends on the achieved thermocline in the tank. Former regulation in Spain [20] recommends the relation given in Eq. 2. Assuming 60ºC for both inlet (Tp) and outlet (Tu) temperatures of the storage system and a supply water temperature (Ti) of 16ºC a conversion factor of 30.73 kWh/m^3 is obtained. Figure 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 show a constant profile along time. So, the first step is to define a demand profile for DHW. In Spain the Technical Building Code [18] does not define such profile but only the water consumption per person and day. A continuous consumption has been assumed between 5 a.m. to 11 p.m., with three peaks overlaid over said continuous consumption, one of two hours long at 7 a.m., and two of one hour long at 3 p.m. and 9 p.m. Figure 2 shows the resulting profile. Other profiles are possible and numerical results will vary according to them. However, the calculation procedure will still be valid.

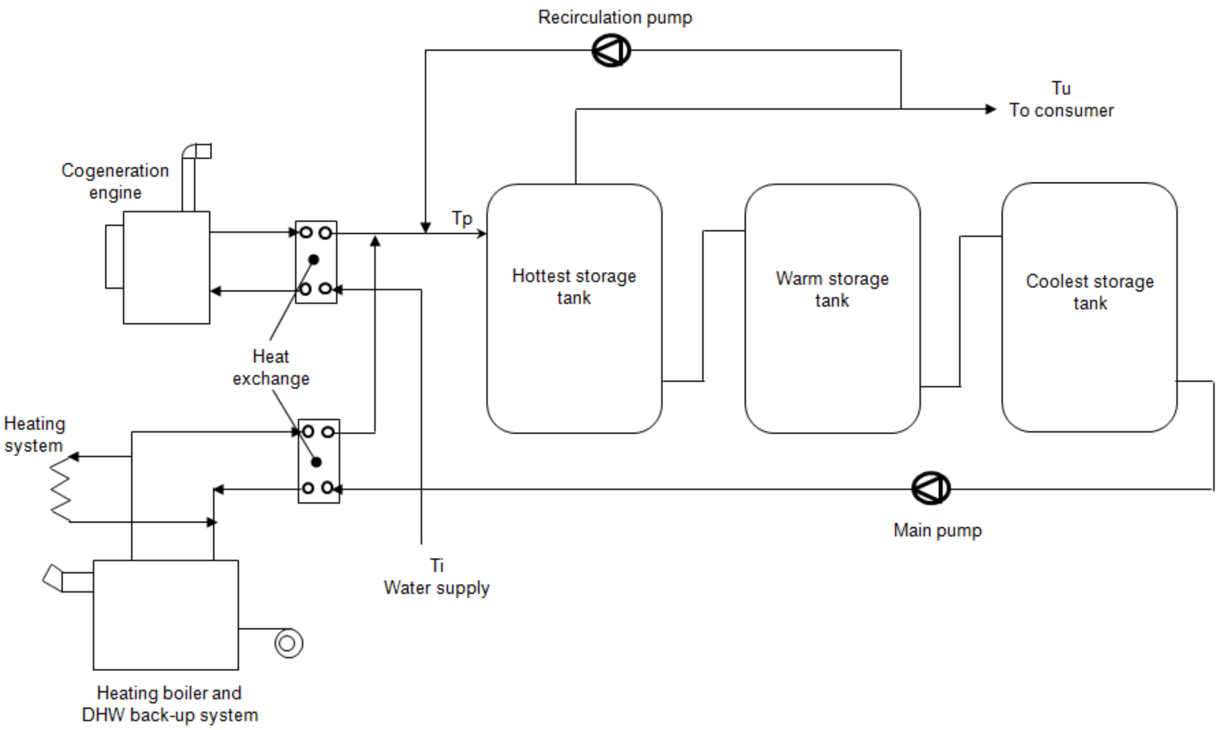

Figure 1: General layout

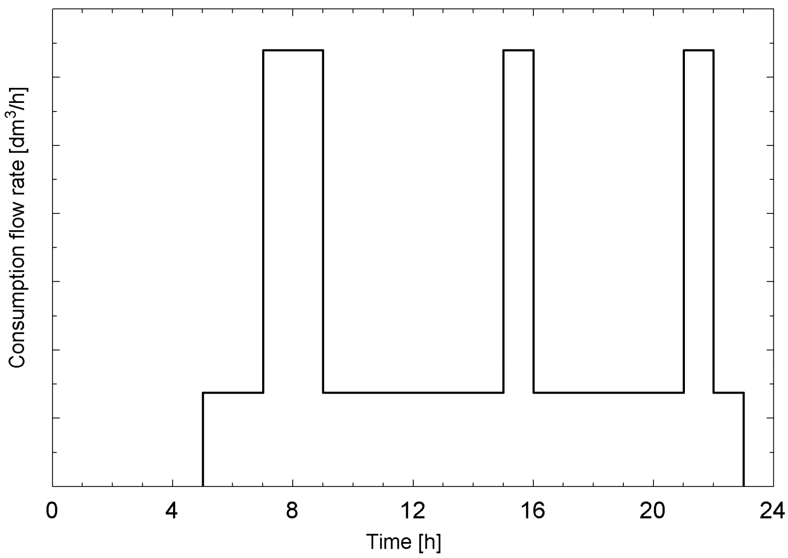

Figure 2: DHW demand profile

The ratio of peak to minimum consumption depends on the number of users (flats). So, the higher the number of users the lower this ratio. Again, Spanish regulation does not impose any ratio so a reasonable relation has been assumed (Figure 3), based again in former Spanish regulations [20]. For a given number of flats Figure 3 determines the peak to minimum consumption ratio and by integration of profile given in Figure 2 it can be calculated the consumption (flow rate) at peak and minimum demand periods when consumption in a day is assumed (22 litres at 60ºC per person and three person per flat [18]).

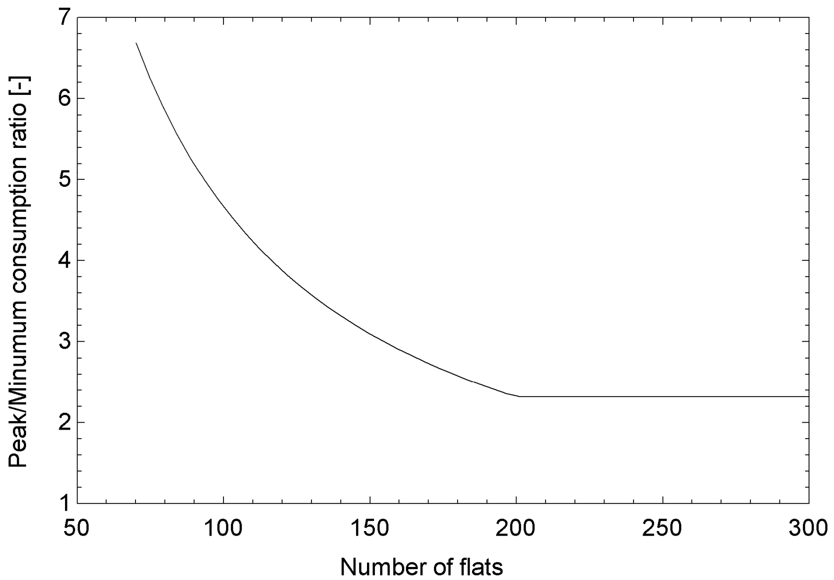

Figure 3: Effect of number of flats in peak to minimum consumption ratio

The calculation procedure of the system includes two phases. The former is the sizing of the storage device; the latter is the evaluation of eventual waste energy and energy supplied by the back-up system (back-up energy).

The sizing phase begins by the calculation of the thermal power taken from the engine, which has to be able to cover the energy demand required to prepare the consumption of DHW in a day. In order to avoid dissipation of thermal energy from the engine this calculation is made at maximum water supply temperature, which is usually known monthly. So, except for the design month, the back-up system is always supplying an amount of energy to complete the thermal demand of DHW preparation.

Sizing calculation is an iterative procedure. So, an initial size ($SE_{\max}$) is assumed. The procedure begins by the application of the energy balance given in Eq. 3 to each period (peak, minimum demand or no consumption). Application of Eq. 3 produces a value of ε_n which, according to Table 1, determines the waste energy, the back-up energy and the stored energy at the end of the n-period, which will be used in the balance in the next period.

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

Table 1: Waste energy, back-up energy and stored energy at n-period depending of variable ε_n given in Eq. 3

	WE_n	BUE_n	SE_n
$\varepsilon_n < 0$	0	$-\varepsilon_n$	0
$0 < \varepsilon_n < 1$	0	0	$\varepsilon_n \cdot SE_{\max}$
$1 < \varepsilon_n$	$(\varepsilon_n - 1) \cdot SE_{\max}$	0	$SE_{\max}$

Once Eq. 3 has been applied to a complete day the overall waste energy and back-up energy can be evaluated. The optimum size of the storage device is the minimum one which produces zero waste energy and back-up energy.

The second phase of the calculation procedure consists in applying the energy balance given in Eq. 3 month by month. So, for each actual water supply temperature the covered percentage of demand and back-up energy are obtained. Due to the design procedure no waste energy is released in any month. Back-up energy is required in order to cover the demand except in the design month.

Combining Eq. 1 and 3 a relation between stored energy at period n-1 and the maximum stored energy is obtained (Eq. 4). Taking into account Eq. 2 it is concluded that the volume of the storage tank is independent from water supply temperature for a given use temperature.

$$SE_{n-1} - \varepsilon_n \cdot SE_{\max} = \left(C_n - \frac{C_d}{24} \right) \cdot t_n \cdot \rho_w \cdot C_w \cdot (T_u - T_i) \quad (4)$$

Experimental facility

An experimental facility has been built to verify the model. A Senertec engine model DACHS HKA-G of 5.5 kWe and 10.8 kWth has been coupled with three tanks of 750 litres each one according to Figure 1, except for the supplementary system which has been removed. The flow rate consumed by 100 flats with the profile shown in Figure 2 has been implemented with programmed electro valves. With flow meters and temperature sensors thermal power recovered from the engine and supplied to the demand has been measured. Nine thermocouples have been used to determine the thermocline in the three tanks, evaluating the stored energy. Figure 3 shows the layout of the experimental facility with the name of the main variables.

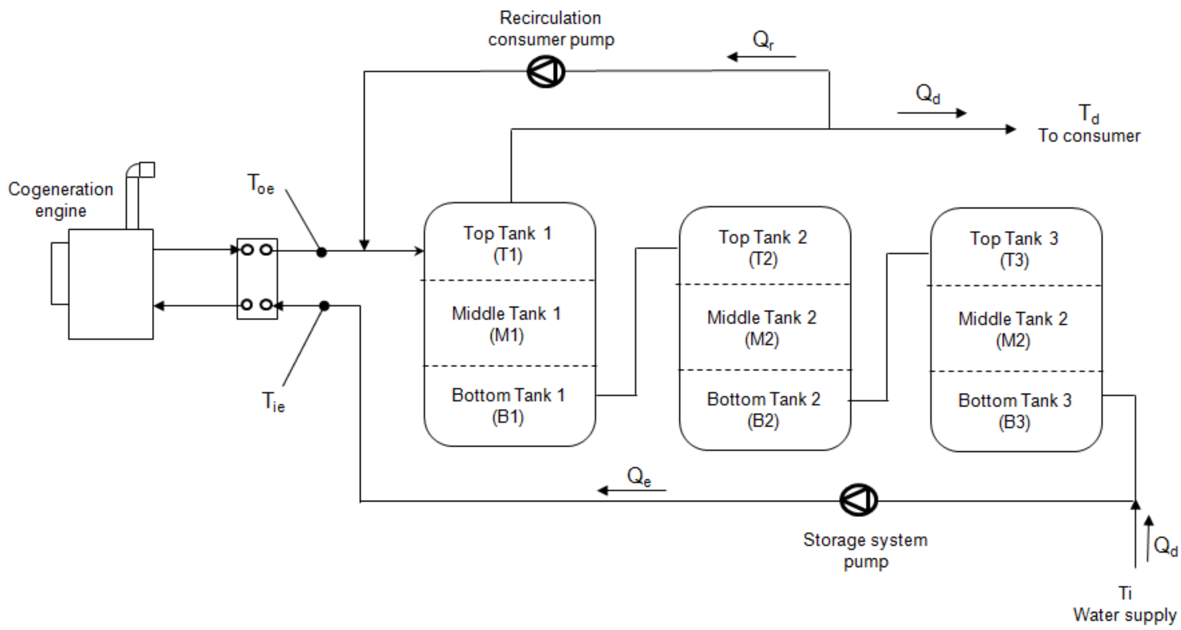

Figure 3: Experimental layout with the name of the main variables

The demand power (H_c), engine thermal power (H_e), power delivered by the system (H_d) and back-up power (H_{bu}) are given by Eqs. 5 to 8. The stored energy in the overall storage volume is evaluated by Eq. 9.

$$H_c = Q_c \cdot \rho_w \cdot C_w \cdot (T_u - T_i) \quad (5)$$

$$H_e = Q_e \cdot \rho_w \cdot C_w \cdot (T_{oe} - T_{ie}) \quad (6)$$

$$H_d = Q_c \cdot \rho_w \cdot C_w \cdot (T_d - T_i) \tag{7}$$

$$H_{bu} = Q_c \cdot \rho_w \cdot C_w \cdot (T_u - T_d) = H_c - H_d \tag{8}$$

$$SE = \frac{V}{9} \cdot \sum_{k=1}^{9} \rho_w(T_k) \cdot C_w \cdot (T_k - T_i) \tag{9}$$

Experimental results have been stored in a data logger and then processed in order to analyse the evolution of power and energy fluxes. Back-up energy is evaluated as the difference between the energy demand and the energy supplied by the cogeneration system (Eq. 8).

Results

Sizing results

Application of Eq. 4 with the consumption profile given in Figure 2 and the peak to minimum demand ratio given in Figure 3 produces Eq. 10.

$$V = (8.179 + 0.3843 \cdot N_f) \cdot (C_{du} \cdot N_p) \tag{10}$$

Eq. 10 gives the minimum volume of the storage tank for a number of flats. This number of flats also determines the maximum engine thermal power from Eq. 1. If actual volume is lower than the one given for Eq. 10 it's necessary to reduce the size (thermal power) of the engine to avoid dissipation of energy or to increase the demand. In this case the engine will not cover the whole demand but there will not be energy dissipation either.

Experimental results

Thermal power supplied by the available engine has been 10.8 kW and overall volume storage tank has been 2,250 litres. Water supply temperature has been 16.8ºC and 3 persons are assumed per flat, with a daily DWH consumption of 22 litres at 60ºC. These data determine different number of flats, so it is necessary to match them.

Number of flats is 68 from Eq. 10 (storage volume) and 78 from Eq. 1 (engine). So, the available storage is lower than the one required for the engine. This means that it would be required to release the thermal energy equivalent to 10 flats. Another possibility is to increase the demand at least in those 10 flats, setting a demand of 88 flats. In order to ensure the release of no thermal energy 100 flats are assumed.

Figure 6 shows the experimental results from the point of view of the evolution of power in time. In Figure 7 the measured stored energy (Eq. 9) in the overall volume is overlaid to the demand power and the thermal power delivered by the system. It is observed that thermal power from the engine is higher that minimum demand, so that storage of energy (charge of energy in tank) occurs in minimum demand periods and in no consumption ones. During peak demand periods the discharge of the thermal energy stored in the tank takes place.

From 23.00 to 5.00, without any demand, the highest storage of energy takes place. From 5.00 to 7.00 (points A to B in Figure 7) the minimum demand reduces the rate of storage and from 7.00 to 9.00 (B to C) the first discharge of the tank takes place. Due to the fact that engine output temperature (an average of 56ºC) is lower than water use temperature a limited back-up power is needed during minimum demand periods, which increases in peak ones. At the end of the first peak period, point C, there is about 7 kWh left in the tank. That is, the back-up system is delivering energy although there is stored energy left. This behaviour is also observed along the whole peak period, with an increasing amount of back-up power as higher as lower stored energy left in the tank.

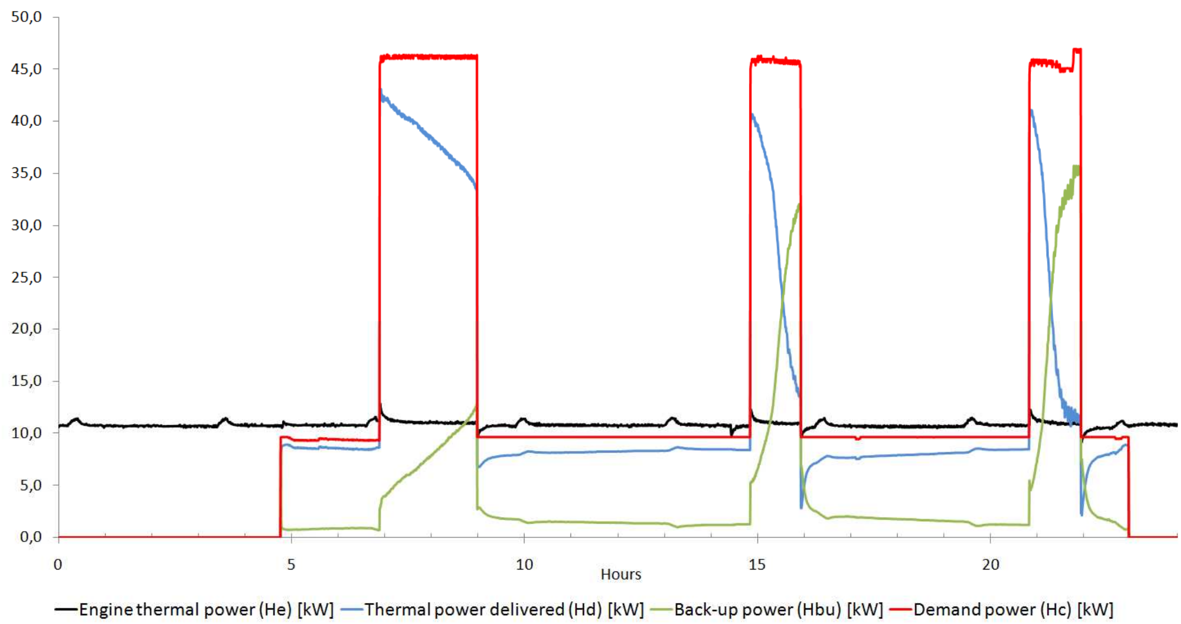

Figure 6: Experimental results (power balance)

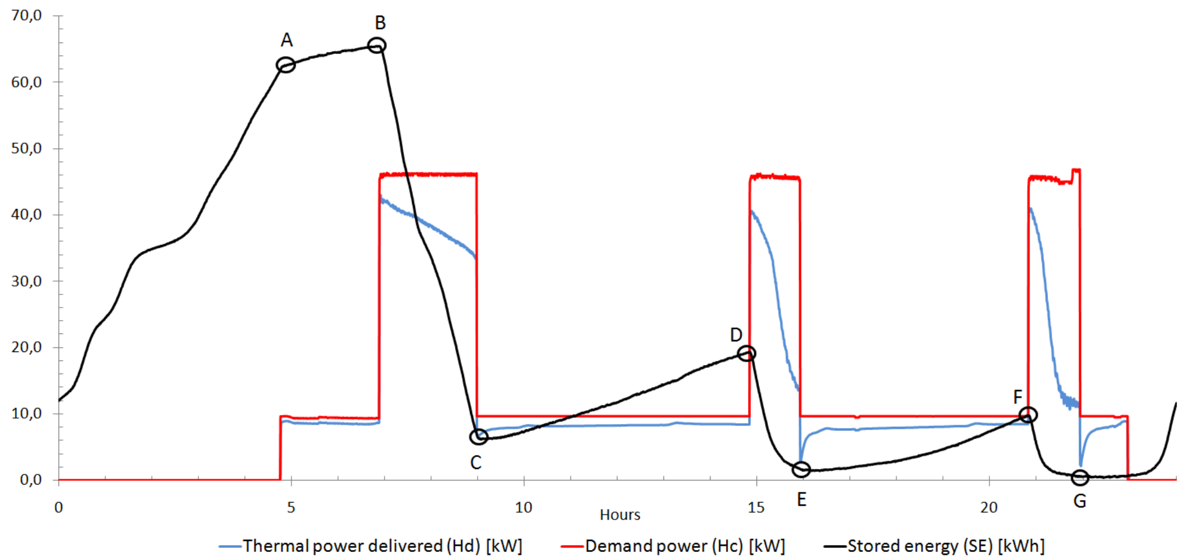

Figure 7: Experimental results (stored energy overlaid to power balance)

The explanation for the supply of energy by the back-up system when there is stored energy left is due to the rate of discharge of that energy. Figure 8 explains the charge and discharge processes. When there is no demand (from 23.00 to 5.00) the highest storage of energy occurs. In this period the water from the bottom of the coolest tank (B3) is sent to the heat exchanger and then sent to the top of the hottest tank (T1). In a minimum demand period the flow rate taken from the water supply is lower than flow rate through the heat exchanger so the thermal power released by the engine is delivered to both the tank and the demand (Figure 7 shows how energy is stored in AB, CD and EF with approximately the same slope). Finally, in a peak demand period the demand flow rate is higher than the heat exchanger one so energy supplied to the demand is taken from both the heat exchanger and the tank.

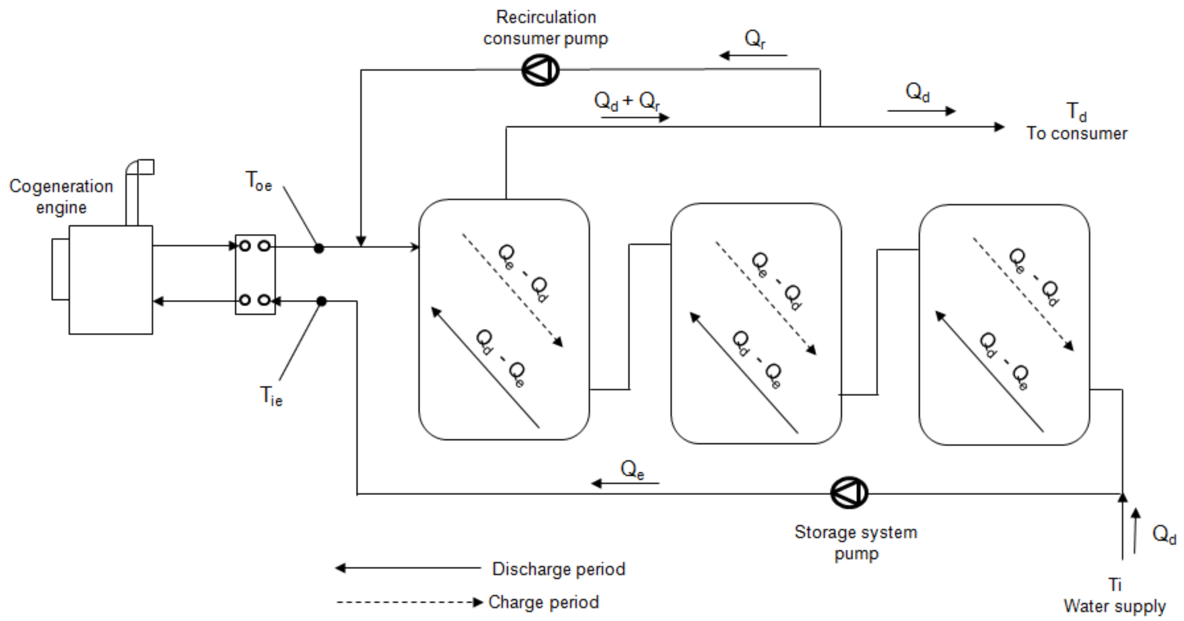

Figure 8: Charge and discharge process

Table 2 shows how the stored energy is distributed along the three tanks in peak demand periods. Table 3 gives the flow rates and duration of these periods. It is possible to explain the stored energy removal process by the pushing effect of the water in the tank from the bottom of the coolest one (B3) to the top of the hottest one (T1). The displaced volume can be evaluated from the flow rate and the duration of the period. This volume, referred to 750/3 litres, is 5.19 for BC, 2.67 for DE and 2.76 for FG periods. Measuring these fractions from T1 in Table 2 it's obtained 57.71 kWh, 17.94 kWh and 9.40 kWh respectively. Removing these quantities from stored energy at the beginning of each period it results 7.79 kWh, 1.36 kWh and 0.30 kWh, which are similar values to the stored energy left in the tank at the end of each period (last row of Table 2). So, the flow rate used to remove the stored energy is the responsible for the remaining stored energy at the end of each peak demand period. This remaining stored energy, not considered in Eq. 3, will cause extra back-up energy.

Table 2: Distribution of stored energy [kWh] during peak demand periods

	B	C	D	E	F	G
T1	11.49	4.19	10.85	0.78	7.91	0.17
M1	11.49	1.65	5.91	0.35	1.27	0.09
B1	11.49	0.70	1.77	0.26	0.29	0.09
T2	11.10	0.12	0.43	0.03	0.09	0.00
M2	10.54	0.09	0.12	0.09	0.03	0.03
B2	8.42	0.09	0.09	0.09	0.06	0.06
T3	0.67	0.06	0.06	0.06	0.03	0.03
M3	0.20	0.09	0.06	0.03	0.06	0.06
B3	0.06	0.03	0.00	0.03	0.00	0.03
Tank	65.5	7.0	19.3	1.7	9.7	0.6

Table 3: Average flow rates and duration of peak demand periods

	BC	DE	FG
Q_e [dm^3/h]	298.5	296.4	285.7
Q_c [dm^3/h]	920.8	913.0	909.3
Q_c-Q_e [dm^3/h]	622.3	616.6	623.7
Duration [h]	2.085	1.08	1.105

It is observed that the flow rate through the heat exchanger changes from minimum demand to peak periods. So, in AB 231.5 dm^3/h are measured, increasing to 298.5 dm^3/h at BC. This increase in the flow rate through the heat exchanger produces lower flow rate trough the tanks, reducing the discharge capacity. This great fluctuation in flow rate is due to the non-existing consumption grid. So, in the experimental facility the hot water produced is drained to atmospheric pressure which perturbs the flow rate distribution. This fact would not take place in a real facility.

From experimental results the actual back-up energy is 81.6 kWh since applying Eq. 4 to nominal values of the experimental case 71.7 kWh is obtained. The difference (9.9 kWh) is according to the sum of the remaining stored energy at the end of each peak demand period (9.3 kWh), due to the restriction imposed to discharge process by the flow rates which would be eventually suppressed in a real installation.

Conclusions

The employment of micro-engines in cogeneration for domestic hot water preparation requires the use of storage energy devices. This paper presents an analytical procedure to estimate the volume of these storage devices when they use the principle of stratified hot water, giving a simple equation for a typical consumption profile. An experimental facility has been built to verify the proposed model. From the results it is concluded that the model obtains good results, being the little differences in support energy evaluation explained by limitations of the facility to represent an actual installation.

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]

H_{bu} : Thermal power supplied by the back-up system to the demand [kW]

H_c : Thermal power to prepare 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 facility [dm^3/h]
SE: Actual stored energy in the tank of the experimental facility [kWh]
$SE_{\max}$: Maximum 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 [ºC]
T_i: Net water temperature [ºC]
T_k: Measured temperature at position k in one tank [ºC]
t_n: n period long [h]
T_p: DHW preparation temperature [ºC]
T_u: DHW use temperature [ºC]
V : Volume of the storage device [dm^3]
WE_n: Waste energy at n period [kWh]

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