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An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in Istanbul

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Abstract

Cold season heating energy requirements in buildings can be estimated with the degree-hours method based on human comfort levels and available meteorological temperature records for a given area. Such estimations are especially significant for cities where fossil fuel consumption must be eliminated in favor of clean energy alternatives to reduce air pollution. This paper considers the city of Istanbul in Turkey and presents a detailed account for practical energy requirements and fuel consumption calculations.

1. Introduction

Seasonal energy consumption calculations are of vital importance in any building design for heating or cooling purposes. There are computer simulation models, based on thermodynamic principles, which are solved numerically by the consideration of initial and boundary conditions in addition to the architectural geometry of the building's usable spaces. However, their use requires a set of assumptions, which are not very realistic in practical applications because weather conditions are rather haphazard and unpredictable. In general, the energy consumption of a building is dependent on three complementary components, namely meteorology, architectural design and material type. The last two components are rather deterministic and controllable. However, the weather conditions are nature-dependent and not controllable in any certain manner. It is,

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Nomenclature

A	glazing area, m^2
c_p	specific heat at constant pressure, kJ/kg K
DH	total number of heating degree-hours
F	total fuel consumption in a city in a heating season, Gm^3
GAP	glazing area percentage, %
H	fuel heating value, J/m^3, J/kg
I	air exchange rates per hour, air changes per hour (ACH), 1/h
L	total heat loss coefficient, W/K
n	number of people living in an apartment building
N	number of hours providing the condition of $\bar{T}_o \leq T_b$ in a heating season
P	population of the city
Q	seasonal heating energy requirement for the prototype apartment building in Istanbul, J
T_b	base temperature, °C
T_i	indoor design air temperature, °C
$\bar{T}_o$	hourly mean of external air temperature, °C
U	thermal transmittance, W/m^2 K
V	total volume of the prototype building, m^3
η	heating-system efficiency, %
ρ	density, kg/m^3

therefore, the weather conditions that cause the uncertainty ingredients, even in the energy requirement level calculations. Consequently, average energy requirement calculations are adopted for energy source allocations. It is to be stressed at this stage that the average degree-hours or degree-days method can not accurately evaluate the impact of thermal mass.

It is the main purpose of this paper to present a case study for the calculations of energy requirement and fuel consumption by considering predetermined architectural components and various number of people living in an apartment building, together with the data obtained from the regular meteorological temperature measurements at a meteorology station. In the cases of both heating and cooling, the energy requirement is determined for a predetermined indoor design temperature in winter and summer. In this paper, a concise method is applied for the prediction of the heating energy requirements in terms of degree-hours [1–5]. The building's heating energy requirements and the fuel consumptions of Istanbul are obtained from the records of hourly air temperature measurements at Göztepe meteorology station and from the knowledge of the thermal characteristics of a chosen typical building, the number of people residing in it and the population of the city. The results are presented in the form of readily usable tables for the city of Istanbul.

2. Degree-hours method

Definitions of degree-time interval, such as degree-hours [1–5], degree-days [6–12] or degree-months are given in the literature. The total number of heating degree-hours for the whole heating season can be expressed as

$$\mathrm{DH}=\sum_{j=1}^{N}(T_{\mathrm{i}}-\bar{T}_{\mathrm{o}})_j \text{ for } (\bar{T}_{\mathrm{o}}\leq T_{\mathrm{b}})_j \tag{1}$$

where T_i and T_b are the constantly adopted indoor design air and base temperatures, $\bar{T}_o$ is the hourly mean of external air temperatures measured at a meteorology station and N is the number of hours providing the condition of $\bar{T}_o \leq T_b$ in a heating season. Therefore, heating degree-hours are calculated when $\bar{T}_o \leq T_b$ [3–5]. The external air temperatures recorded at Göztepe meteorology station during the period of 1990–1997 are used to calculate the hourly means over the given years of the external air temperatures, $(\bar{T}_o)_j$ for each day in the heating season. For each hour of the day, the variations of the total duration and total number of heating degree-hours in the heating season providing $(\bar{T}_o)_j \leq T_b$ and, hourly means of external air temperatures over the heating season are indicated in Fig. 1. The total number of heating degree-hours is estimated DH=55103.6 degree-hours for the heating season in Istanbul by the aid of Fig. 1 and Eq. (1).

The base temperature corresponds to the human comfort requirements and varies from one location to another, which affects the start date of building heating season. In general, it is also possible to adjust T_b within each time interval as desired but, in practical studies, it is adopted most often as a constant [1–12]. The base and the indoor design air temperatures, which are kept constant, are adopted as they are used for Germany [3–5] as T_b=15°C and T_i=20°C, respectively, together with a set of $\bar{T}_o$ varying in time for this study. In some studies, T_b is the temperature at

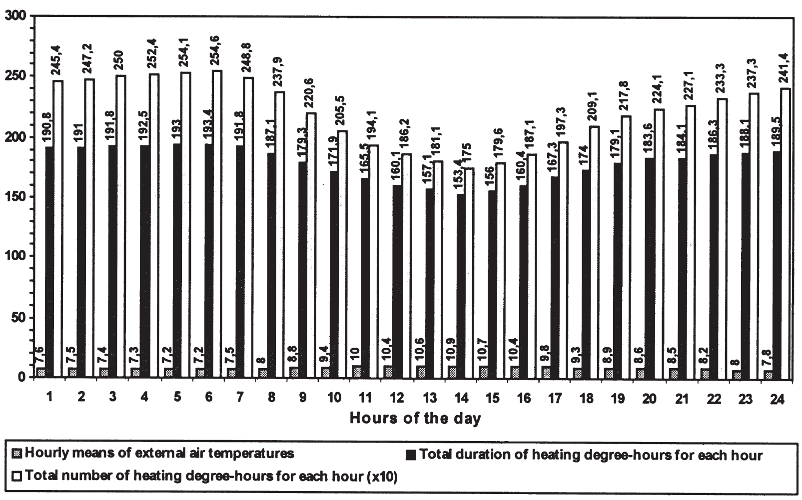

Fig. 1. For each hour of the day, the variations of the total duration (h) and total number of heating degree-hours in the heating season providing $(\bar{T}_o)_j \leq T_b$ and, hourly means of external air temperatures (°C) over the heating season for Istanbul.

which the building heat losses are equal to the gains which can be represented by $T_b=T_i$ [1,2,6–12]. By using this consideration, a detailed account of degree-days concept is presented by Thom [7,8].

3. Practical calculations and interpretations

The following calculations, based on the air temperature records of Göztepe meteorology station beginning in 1936, are presented for Istanbul and they can be repeated similarly for any part of the world.

The prototype, 10 story apartment building, in which it is assumed that 20, 25, 30, 35, 40, 45, 50, 55 or 60 people may live, is located on the Asian side of Istanbul just near the Göztepe meteorology station. It is assumed that the indoor temperature T_i=20°C is maintained in each space of the prototype building. The outside dimensions, width×depth×height, of this building are considered as 20×11×14 m. The depth of the foundation wall below ground is 1.8 m and the narrowest width of the building is 11 m. The thermal transmittance U of the basement floor is chosen as 0.12 W/m^{2}K [13].

According to ASHRAE [13], the annual 99.6% outdoor design conditions for Istanbul are: the heating dry-bulb temperature is −3.2°C, extreme wind speed is equal to 11.8 m/s; the location of Göztepe is: 40.47 North latitude, 28.82 East longitude and 37 m altitude.

The daily outdoor air temperature variation, based on the records of Göztepe meteorology station, is illustrated along with a fitted polynomial function of the 7th order in Fig. 2. In this study, Fig. 2 is used only for determination of the start and end of the heating season. The 292nd

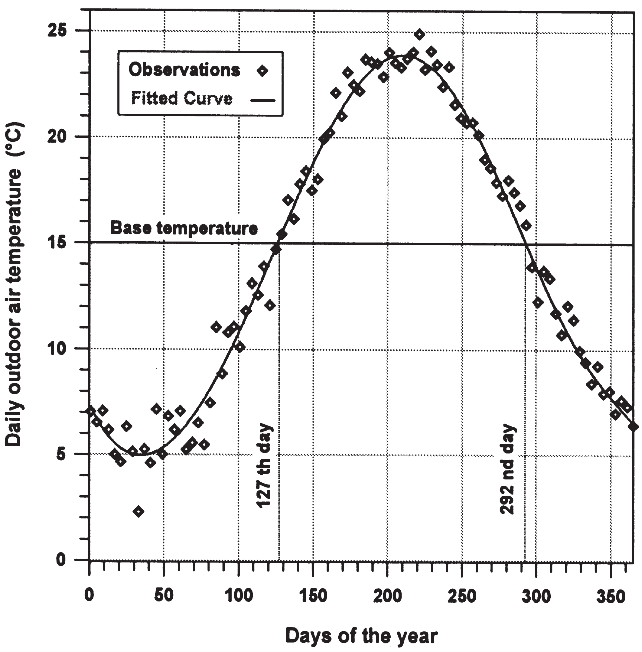

Fig. 2. Daily outdoor air temperature variation for Istanbul.

day (19 October) and 127th day (7 May) of the year appear as the beginning and end of the heating period in Istanbul if T_b=15°C is adopted.

The daily mean heating degree-hours based on T_b=15°C are shown in Fig. 3. It is obvious from Figs. 2 and 3 that there is no need for heating between the 127th and 292nd days of the year. From Figs. 2 and 3, it is possible to conclude that, in subtropical regions, parabolic daily degree-hour variations occur. The span of parabolic daily mean degree-days becomes narrower at higher latitudes but wider as the location becomes closer to the equator.

Physical and thermal properties for the building construction materials are shown in Table 1. The values given in this table provide the basic data for the calculation of the overall thermal resistance value for the roof and the outside walls of the building. With the numerical values given in Table 1, the overall thermal resistance for the ceiling under the roof turns out to be 1.415 m^2K/W. The thermal transmittance is defined as the reciprocal of the overall thermal resistance and it is equal to 0.707 W/m^2K for the ceiling under the roof and 0.8626 W/m^2K for the outside walls. A brief summary of the *U*-factors for the ceiling under the roof, the outside walls, the windows and the basement are also presented in Table 1.

According to ASHRAE [13], natural ventilation is the flow of outdoor air due to wind and thermal pressures through intentional openings in the building's shell. Natural ventilation openings include, (1) windows, doors, dormer (monitor) openings, and skylights; (2) roof ventilators; and (3) specially designed inlet or outlet openings. Infiltration is the rate of uncontrolled air exchange through unintentional openings that occur under given conditions, while air leakage area is a measure of the airtightness of the building shell. The greater the air leakage area of a building, the greater its infiltration rate. Let us assume that the seasonal average air exchange rates per

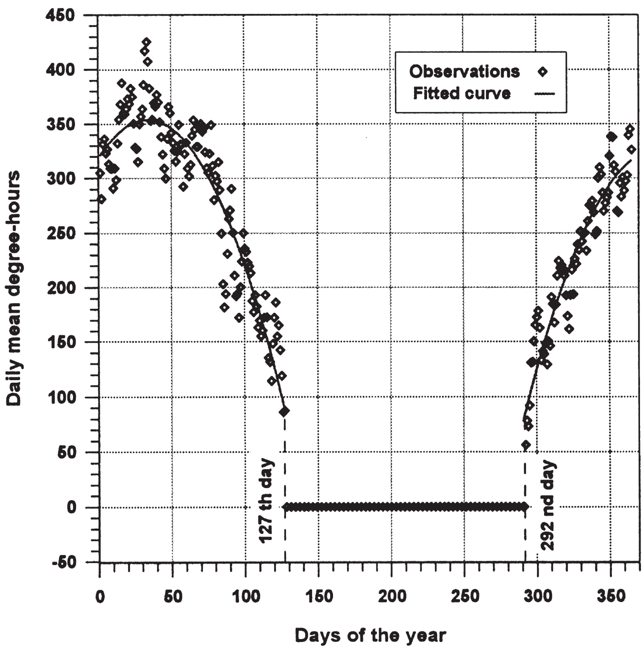

Fig. 3. Daily mean degree-hours for Istanbul.

Table 1
Physical and thermal properties of building construction materials [13,15]

Element	Area (m^2)	Material	Conductivity (W/mK)	Thickness (m)	*U*-factor (W/m^2K)
Ceiling under the roof	220	Glass fiber	0.038	0.05	0.71
		Concrete with sand and gravel aggregate	2.1	0.15	
		Cement plaster with sand aggregate	0.72	0.02	
Outside walls	868 minus glazing area	Cement plaster with sand aggregate	0.72	0.02	0.86
		Brick, fired clay	0.405	0.09	
		Perlite, expanded	0.0485	0.02	
		Brick, fired clay	0.405	0.19	
		Cement plaster with sand aggregate	0.72	0.02	
Windows	20, 30, 40, 50% of outside walls	Single glass			5.91
		Double glass			3.46
Basement	220				0.12

hour, *I* (ACH), due to the ventilation and infiltration for our example building may be I=0.5 ACH, 1.0 ACH, 1.5 ACH, and 2.0 ACH. In addition to this, the glazing area, *A*, may be 20% (173.6 m^2), 30% (260.4 m^2), 40% (347.2 m^2), and 50% (434.0 m^2) of the total outside wall area. The roof, outside wall, and floor areas follow 220 m^2, 868 m^2, and 220 m^2 and the total volume of the building is V=3080 m^3. Thus, the total heat loss coefficient of the prototype building, *L* (W/K), for single and double glass, various glazing area percentage of outside walls, GAP, and *I* is calculated as

$$L=\sum UA+I(\rho c_p)_{air}V/3.6=\sum UA+IV/3 \quad (2)$$

since the volumetric thermal capacity of air is $(\rho c_p)_{air}$=1.2 kJ/m^3K [13]. Then, the results are presented in Table 2.

The seasonal heating energy requirements, *Q* (J), for the prototype apartment building in Istanbul for DH=55103.6 degree-hours are estimated as

Table 2
Building heat loss coefficient *L* (W/K) for various glazing type and surface area GAP, and air infiltration rate *I*

GAP (%)	Single galss				Double glass			
	0.5 ACH	1.0 ACH	1.5 ACH	2.0 ACH	0.5 ACH	1.0 ACH	1.5 ACH	2.0 ACH
20	2470.0	2983.3	3496.7	4010.0	2044.7	2558.0	3071.3	3584.7
30	2983.0	3496.3	4009.6	4523.0	2345.0	2858.3	3371.7	3885.0
40	3496.0	4009.3	4522.6	5036.0	2645.3	3158.7	3672.0	4185.3
50	4009.0	4522.3	5035.6	5549.0	2945.7	3459.0	3972.3	4485.7

Table 3
Estimations of the heating energy requirements Q (GJ) of an apartment building in Istanbul

GAP (%)	Single glass				Double glass			
	0.5 ACH	1.0 ACH	1.5 ACH	2.0 ACH	0.5 ACH	1.0 ACH	1.5 ACH	2.0 ACH
20	490.0	591.8	693.6	795.5	405.6	507.4	609.3	711.1
30	591.7	693.6	795.4	897.2	465.2	567.0	668.8	770.7
40	693.5	795.3	897.2	999.0	524.8	626.6	728.4	830.3
50	795.3	897.1	998.9	1100.8	584.3	686.2	788.0	889.8

$$Q = 3600L\ \mathrm{DH} \tag{3}$$

then, the results are given in GJ in Table 3 for single and double glass, various GAP and I.

The relationships between the building architectural design properties and Q are given in Figs. 4 and 5. Fig. 4 illustrates the seasonal heating energy requirement for the prototype apartment building in Istanbul, together with the equations for both single and double glasses, vs GAP. Similarly, Fig. 5 exhibits the seasonal heating energy requirement for the prototype apartment building in Istanbul vs I.

Another significant factor is the number of people, n, living in an apartment building which determines the number of buildings in a city if the population of city is considered constant and assumed to live only in apartment buildings. Total fuel consumption in a city for building heating purpose in a heating season can be expressed as

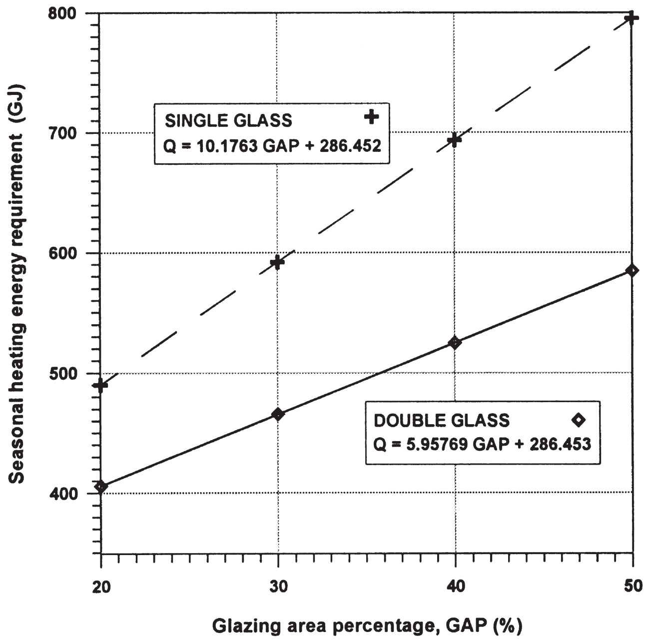

Fig. 4. Seasonal heating energy requirement for the prototype apartment building in Istanbul for I=0.5 ACH vs glazing area percentages.

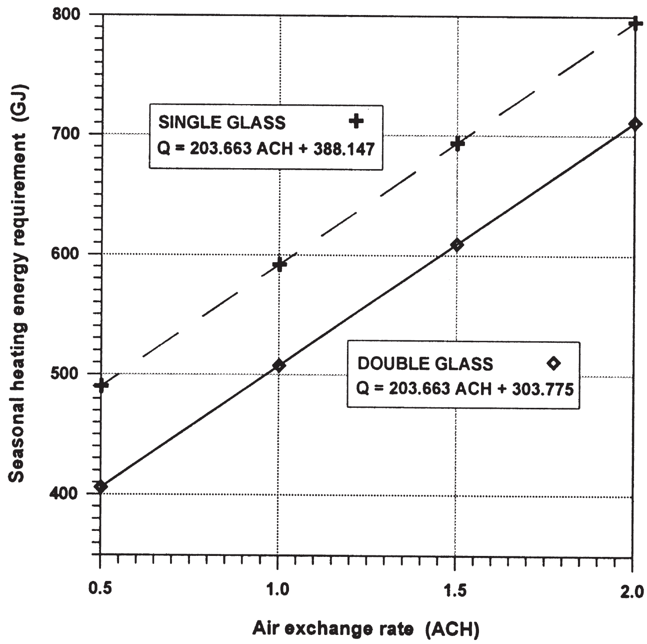

Fig. 5. Seasonal heating energy requirement for the prototype apartment building in Istanbul for GAP=20% vs air exchange rates.

$$F=\frac{QP}{\eta Hn}. \tag{4}$$

In Eq. (4), H is the fuel heating value, η is the heating-system efficiency so called the thermal efficiency of the burning equipment, and P is the population of the city; the heating-system efficiency is defined as the ratio of the thermal output from the heating system divided by the energy input averaged over the time period of the analysis.

In this case study, the following assumptions are used: the population of Istanbul is 9,198,809 people, the heating value of natural gas H=36.79 MJ/m^3 [14] and the thermal efficiency of 0.92. The number of people living in an apartment building is used as a parameter in this study, with values between 20 and 60. Table 4 summarizes the estimations of natural gas consumption for the heating season in Istanbul, in the case all heating energy requirements are supplied by natural gas depending on single or double-glazing, various GAP and n. Similar predictions are made for coal considering H=25.12 MJ/kg and η=0.72, and for fuel oil considering H=41.87 MJ/kg and efficiency of 0.82 [15].

Again considering apartment buildings with 0.5 ACH, the total natural gas consumption in Istanbul for the building heating purpose in the heating season is shown in Fig. 6. The total fuel consumption decreases as the number of people living in an apartment building increases, because the number of buildings decreases and assuming the population of city is constant (see Fig. 6). The relationships for extreme cases, which are the best and worst conditions, again for the natural gas consumption are presented in Fig. 7.

According to a study reported by Istanbul Natural Gas Distribution Company [16], the total

Table 4
Estimation for the natural gas consumption (Gm^3) for the heating season in Istanbul in case all heating energy requirements are supplied by natural gas

No. of people living in an apartment building	GAP (%)	Single glass				Double glass			
		0.5 ACH	1.0 ACH	1.5 ACH	2.0 ACH	0.5 ACH	1.0 ACH	1.5 ACH	2.0 ACH
20	20	6.7	8.0	9.4	10.8	5.5	6.9	8.3	9.7
	30	8.0	9.4	10.8	12.2	6.3	7.7	9.1	10.5
	40	9.4	10.8	12.2	13.6	7.1	8.5	9.9	11.3
	50	10.8	12.2	13.6	15.0	7.9	9.3	10.7	12.1
25	20	5.3	6.4	7.5	8.6	4.4	5.6	6.6	7.7
	30	6.4	7.5	8.6	9.8	5.1	6.2	7.3	8.4
	40	7.5	8.6	9.8	10.9	5.7	6.8	7.9	9.0
	50	8.6	9.8	10.9	12.0	6.4	7.5	8.6	9.7
30	20	4.4	5.4	6.3	7.2	3.7	4.6	5.5	6.4
	30	5.4	6.3	7.2	8.1	4.2	5.1	6.1	7.0
	40	6.3	7.2	8.1	9.0	4.8	5.7	6.6	7.5
	50	7.2	8.1	9.0	10.0	5.3	6.2	7.1	8.1
35	20	3.8	4.6	5.4	6.2	3.1	3.9	4.7	5.5
	30	4.6	5.4	6.2	7.0	3.6	4.4	5.2	6.0
	40	5.4	6.2	7.0	7.8	4.1	4.9	5.7	6.4
	50	6.2	7.0	7.8	8.5	4.5	5.3	6.1	6.9
40	20	3.3	4.0	4.7	5.4	2.8	3.4	4.1	4.8
	30	4.0	4.7	5.4	6.1	3.2	3.9	4.5	5.2
	40	4.7	5.4	6.1	6.8	3.6	4.3	4.9	5.6
	50	5.4	6.1	6.8	7.5	4.0	4.7	5.4	6.0
45	20	3.0	3.6	4.2	4.8	2.4	3.1	3.7	4.3
	30	3.6	4.2	4.8	5.4	2.8	3.4	4.0	4.7
	40	4.2	4.8	5.4	6.0	3.2	3.8	4.4	5.0
	50	4.8	5.4	6.0	6.6	3.5	4.1	4.8	5.4
50	20	2.7	3.2	3.8	4.3	2.2	2.8	3.3	3.9
	30	3.2	3.8	4.3	4.9	2.5	3.1	3.6	4.2
	40	3.8	4.3	4.9	5.4	2.9	3.4	4.0	4.5
	50	4.3	4.9	5.4	6.0	3.2	3.7	4.3	4.8
55	20	2.4	2.9	3.4	3.9	2.0	2.5	3.0	3.5
	30	2.9	3.4	3.9	4.4	2.3	2.8	3.3	3.8
	40	3.4	3.9	4.4	4.9	2.6	3.1	3.6	4.1
	50	3.9	4.4	4.9	5.4	2.9	3.4	3.9	4.4
60	20	2.2	2.7	3.1	3.6	1.8	2.3	2.8	3.2
	30	2.7	3.1	3.6	4.1	2.1	2.6	3.0	3.5
	40	3.1	3.6	4.1	4.5	2.4	2.8	3.3	3.8
	50	3.6	4.1	4.5	5.0	2.6	3.1	3.6	4.0

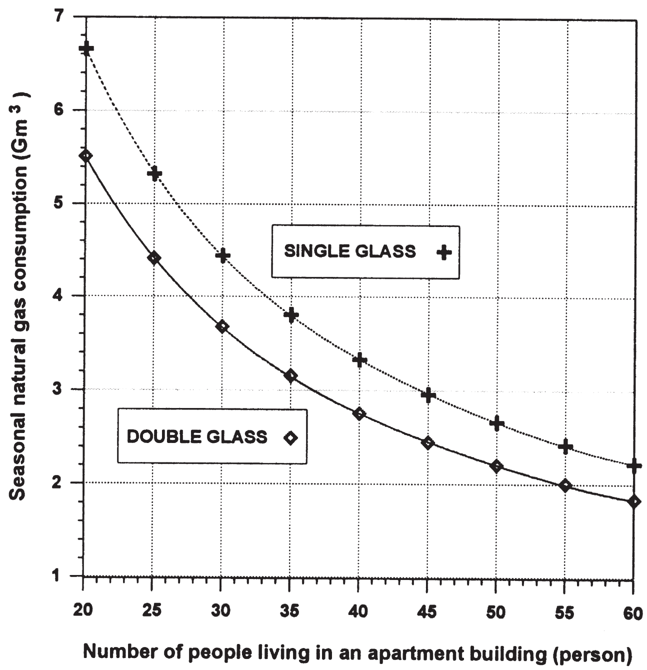

Fig. 6. Seasonal natural gas consumption in Istanbul for GAP=20% and I=0.5 ACH vs number of people living in an apartment building.

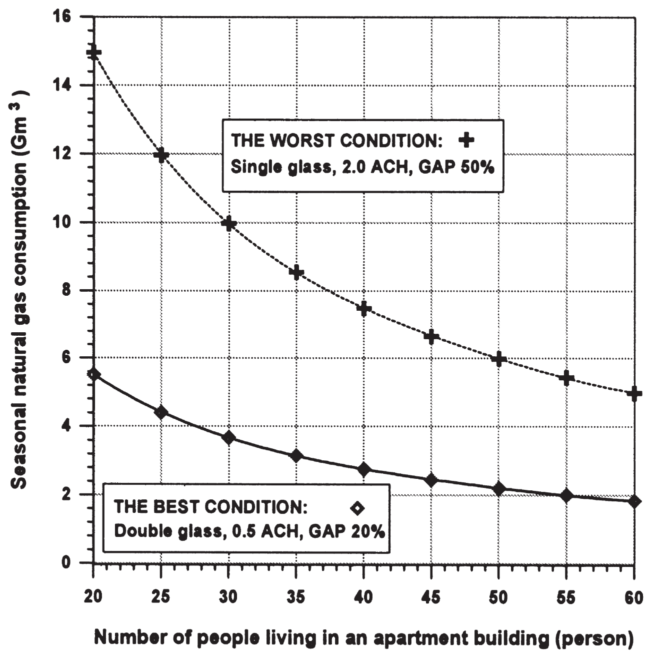

Fig. 7. Seasonal natural gas consumption in Istanbul for the best and worst construction conditions vs number of people living in an apartment building.

natural gas consumption for residential heating in Istanbul in 1998 is almost 1.86 Gm^3. This amount expresses that about 50% of the whole fuel consumption for residential heating in Istanbul. The best and worst conditions in Fig. 7 and values in Table 4 are based on the estimation for the natural gas consumption for the heating season in Istanbul in case all heating energy requirements are supplied by natural gas only. By assuming that on the average there are five to six individuals in a family and accordingly there are 50–60 individuals in each apartment in Istanbul, it is possible to calculate approximately from the average of two curves in Fig. 7 that 4–3.3 Gm^3 of natural gas consumption is possible. Finally, 50% of this amount is approximately equal to 1.86 Gm^3 as the prediction. Therefore, it is then realized that the calculations in this paper verify that the estimations are in good agreement with the reality if 50% of the values in Table 4 and Fig. 7 are considered.

4. Conclusions

This paper presents a case study of residential heating energy requirement estimation for the prototype apartment building and fuel consumption estimation for the city of Istanbul, based on temperature records at Göztepe meteorology station on the Asian side of Istanbul. This area is a representative for subtropical regions. Heavy air pollution episodes during heating periods forced the city to switch to natural gas. It is observed that the heating period in a year starts on 292nd day (19 October) and ends on 127th day (7 May) which lasts for 201 days. The maximum daily mean external air temperature appears on about 210th day, which corresponds to 29 July. The heating energy requirement and fuel consumption calculations are based parametrically on single and double-glazing, various type of material used, I, n, P, GAP and DH. The estimation method based on the air temperature records used in this paper for Istanbul can easily be applied similarly for any part of the world.

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