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"OPTIMIZATION OF SOLAR COLLECTOR SIZE TO ACHIEVE THE HEAT REQUIREMENT ALONG CERTAIN PERIOD"

BY

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ABSTRACT

This paper presents a complete analysis and a numerical application for deducing the optimum solar collector size to satisfy the heat requirement per year for certain estimated life-time of the heating system. Total cost of the heating systems (collector and auxiliary one) is computed for various collector areas. The collector area corresponding to the minimum total cost yields the optimum collector size. This goal is very significant since with increasing collector size, the solar contribution will be greater but certain heat collected will wasted if there is no simulataneous demand. On other hand, it is unequivocal that a small collector of only a few square metres would be utilized all year round. Various collector cost functions are assumed to establish its influence on both optimum and maximum collector size beyond which the estimated life-time cost would be more than that a conventional one.

Annual net solar contributions for different collector areas are computed. The behaviour of utilization rate and figure of merit for various areas of collector is explained and researched.

Eventually, this article reveals the effect of the capital cost of the collector size on the optimum and maximum collector areas.

1. INTRODUCTION

The purpose of attaining the optimum collector size is very significant since it achieves both the technical (heat requirement through certain period, say, year) and the economical (minimum costs of the heating system) constraints. The heating system includes solar collector and an auxiliary heating system.

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Much of radiant energy is absorbed when it falls on a matt black surface. This absorption depends on the type of absorber material. This complex phenomenon includes scattering, photon absorption, acceleration of electrons, multiple collisions, but the final influence is that this radiant energy of all wavelengths is degraded to heat. The temperature increases since the molecules of the surface will be excited. The absorption coefficient of the several types of black absorbers varies from 0.8 to 0.98. By the effect of conduction, some of this molecular movement (i.e. heat) is transmitted to other parts of the body, and some of it is re-emitted to the environment by convective and radiant processes.

The differece in temperature between the surface and the environment affects this emission of heat. The equilibrium temperature is reached when the rate of radiant heat input is equalled by the heat loss. If the surface of the absorber plate is covered by a sheet of glass with certain air space (20 → 30mm) the heat loss is considerocbly reduced without much decreasing in the heat input. This is because of the selective transmittance of the glass. For short wave,it is highly transparent i.e. high temperature solar radiant, however, it is opaque for longer wavelength infra-red radiation emitted by the absorber plate below 100 °C. The glass causes some decrease of the radiation intensity on the absorber plate. This means that there is an optical loss in transmission. However, this is much less than the resultant saving on heat loss. The proportion transmitted is expressed by the transmission coefficient which has a constant value for diffuse radiation, although for direct radiation, it is a function of the angle of incidence.

Some 25% of all energy consumed is used for the heating of buildings and domestic hot water. The lowest grade of energy is required for the space and water heating. With low temperature collection, the highest collection efficiencies are obtainable.

A tracking mechanism is required for the focusing devices and respond to direct radiation only. Flat plate collectors can utilize both diffuse and direct radiation and may be fixed in one particular position. They replaces an enclosing element such as a wall or a roof i.e. they may become part of the building envelope.

2. OPTIMIZATION OF THE SOLAR COLLECTOR SIZE WITH THE REQUIRED CONSTRAINTS:

2.1. Flat Plate Collectors

If a certain thermal fluid (e.g. air or water) is circulated as a carrying medium in thermal contact with the absorber plate, then it will be heated and thus some of the heat absorbed by the plate will be removed. Then, the temperature of the plate is roduced to below the equilibrium temperature and this will decrease the heat loss.

The solar collector plate itself can be any metal sheet, incorporating water channels. It may be-in its simplest case-an ordinary central heating radiator panel. Many steel, copper an aluminium products are on the market which may be suitable.

Some form of header or manifold connects tne water channels at top and bottom. The header should have a cross sectional area larger than the aggregate area of the channels served to ensure a balanced and uniform flow in all channels.

Surface finish of the absorber plate may be a matt black paint such as a chalk-bourd. black, with an appropriate rust inhibiting primer.

The so-called "selective surfaces have a high absorption and emission coefficient for the 200-2000 nm solar radiation, but a much lower a and e value for the longer infra-red (up to 20000 nm) emitted by bodies at a temperature below 100°C. The a/e ratio is a measure of their performance i.e. the ratio of absorption coefficient for solar radiation to the emission coefficient at operating temperatures.

2.2. Annual Heat Requirement

The annual heat requirement of a certain building will depend on the following two factors:

a) The climatic parameters

The climate can be characterized by the degree-day concept. This can be expressed as the annual cumulative temperature deficit which is the sum of the products of temperature differences and their duration.

A reference level is taken as indoor temperature (t_i)(say 18°C). For every day, the mean outdoor temperature (t_o) is established and then the temperature difference is taken as ($t_i - t_o$). If, for example, the mean (t_o) is 2°C for three days, $3 \times (18 - 2) = 48$ degree-days are added to the sum. This is calculated for all days of the year, whenever the t_o is less than the reference level. If these values are multiplied by 24, we have the required climatic parameter in a more convenient form: the number of degree-hours (degc.h.)

b) The building parameter

The building will be characterized by the specific heatloss rate concept. This rate is the total heat loss rate per unit temperature different. The total heat-loss is the sum of two components:

1- The heat loss rate through the building envelope (Q_c) can be expressed as

$$Q_c = (\sum A \times U)\Delta t$$

where

A = area of each element (m^2)
U = thermal transmittance of each element(W/m^2 degc)
Δt = temperature difference (degc).

and

2- The ventilation heat loss (Q_v) and is given by

$$Q_v = 0.36 \times V \times N \times \Delta t$$

where

V = volume of space (m^3)
N = Number of air changes/h
Δt = temp. difference (degc).

$$Q(\text{Total heat loss}) = Q_c + Q_v$$

$$= ((\sum A \times U) + 0.36 \times V \times N)\Delta t$$

$$\text{The specific heat loss rate} = \frac{Q}{\Delta t}$$

$$= (\sum A \times U) + 0.36 \times V \times N$$

Dimensionally Ventilation rate in $\frac{m^3}{h}$

$$\frac{W}{degc} = m^2 \frac{W}{m^2\ degc} + \frac{Wh}{m^3\ degc} \cdot \frac{m^3}{h}$$

For a small well insulated house, the value of this may be as low as 200 W/degc and as much as 1000 W/degc for a large loosely planned residence.

The annual heating requirement is the product of the two parameters: the degree-hours and the specific heat loss rate

$$\frac{W}{degc} \times degc.h = Wh$$

If a combined space and water system is considered, we add the water heating requirement to the above value. The water heating requirement will be the product of the daily hot water consumption, 365, the specific heat of water (1.16 Wh/litre x degc) and the increase from cold supply temperature to the required hot water temperature.

2.3. Solar contribution, figure of merit, and utilization rate.

The supply of the solar heat is out of phase with the heating demand. Much of the energy available in the summer will be wasted, as there is no simultaneous demand. However, the collection system will be self-regulating to some extent: i.e. there is no further collection when the water temperature reaches the stability point i.e. the heat loss from the collector will equal the solar gain.

The following seven parameters influence the amount of energy usefully collected: incident energy, optical loss through transparent cover, absorption properties of the receiving surface, heat transfer properties of the absorber from surface to fluid i.e. the plate effeciency, thermal transmittance of transparent cover, which is a factor of heat loss, collection temperature which depends on: the fluid flow rate and the fluid temperature at entry to collector, and the external air temperatures.

The collection efficiency (ratio of the utilized energy to incident energy) will be affected by these parameters. It may be as high as 70% but it can be as low as 30%.

It is suitable to assume an average collection efficiency of 30% for the heating season with collection temperature about 40 → 50°C for the purposes of a crude estimate.

The intensity of radiation uniformly varies, however, the cumulative total for a day or even for a month will provide a sufficient basis for an estimate.

The average monthly totals are measured on a horizontal plane, and totals for a vertical south facing wall are calculated in addition for an optimally tilted plane for the site under consideration.

If we tabulate these values of radiation for certain site, we can easily remark that, there is a certain constant ratio on average between the energy received by the optimally tilted plane and that of the horizontal one. Then if the values for a horizontal plane are multiplied by the product of this ratio and the assumed 30% efficiency which would yield the amount of collected energy for the period taken (say, one month). Then, total collection energy is computed for each month by multiplying the preceding unit collection energy (in KWh/m^2) by the solar collector area in m^2.

The effective solar contribution is given by the total collection energy in KWh but not more than the space heat requirement in KWh.

The highest collection efficiency does not necessarily mean the most economic system since this high efficiency can often only be achieved by a very expensive installation. Then a balance must be found between capital expenditure and resultant savings in running costs.

Figure of merit (FM) is a useful expression of this cost-effectiveness of an installation.

$$FM = \frac{\text{Value of energy saved by the install. in certain period}}{\text{Extra cost of installation over a convent. one}}$$

The system will be competitive if the figure of merit reaches a value of 1- in certain proposal-i.e. if, say, 10 years energy saving will equal the capital cost. FM, simply, gives a convenient comparative value. The energy saved is determined by establishing first the annual heat requirement, the amount of energy actually contributed by the solar collector and eventually this must be given a monetary value per KWh which depends on the type of fuel. FM is, then given by dividing the monetary value of the energy saved (or solar collected energy) in the periods assumed (5, 10 and 15 years) by the extra cost of the solar heating system which is given by the product of the collector cost (£/m^2) by the collector area in m^2.

The utilization rate is assigned by the ratio of the cumulative net solar contribution along the year and the total collected energy by the collector considered. For certain heat demand during a period of, say, one year, the utilization rate decreases as the solar collector area increases.

2.4. Numerical application

This application reveals that an important amount of the heat collected will be wasted as there is no simultaneous demand. It is clear that a small collector of only a few square metres would work all year round; there would be a demand at all times for the heat it produces (It is used for water heating as well as space heating) we say, then, that its utilization rate would be one. Its total contribution or its portion of the total heat demand would be small. By increasing the collector size, the contribution will be greater and the utilization rate would be reduced.

The deduction of the optimum collector size can be established by the minimization of the total cost of the expected life-time of the heating system.

The following features are taken into consideration:

1) The collection cost is assumed to have linear function with different slopes (£ 10/m^2 and £ 15/m^2) to derive the sensitivity of the optimum collector size to these variations.

2) The expected life-time of the auxiliary heating system is assumed to have various years (5, 10 and 15) to get its influence on the optimum collector size.

3) Several types of fuel used in the auxiliary heating system are taken to investigate what type that yields minimum total cost.

4) The problem is researched for different values of the specific heat loss rate of the house (0.2 KW/degc → 1.0KW/degc). The values taken are 0.25, 0.50, and 1.0 KW/°C.

5) The annual set solar contribution with various areas of collector is calculated.

6) It is assumed that the optimally tilted plane receives about 1.5 times as much energy as the horizontal surface.

Table (1) yields the average monthly cumulative totals of the radiation of certain site measured on a horizontal plane and the calculated totals for a vertical south facing wall as well as for an optimally tilted (34°C) plane at the country chosen.

Table (1)

Month	Horizontal (KWh/m^2)	South vertical KWh/m^2	South 34° tilt KWh/m^2
Jan	18.3	30.3	29.4
Feb.	30.9	47.3	51.6
Mar.	60.6	61.8	81.8
Apr.	111.9	75.9	137.1
May	123.2	57.2	133.2
Jun.	150.4	53.8	155.7
Jul.	140.4	53.6	142.1
Aug.	125.7	69.1	141.1
Sep.	85.9	75.2	111.2
Oct.	47.6	62.8	72.8
Nov.	23.7	41.2	40.5
Dec.	14.4	22.6	22.2

This table is suited for all cases that under research. The collection efficiency is assumed to be 30%.

Case 1- Specific heat loss rate = 0.25 KW/oc.

Table 1.1 reveals the calculation of the effective solar contribution. The site under investigation has an annual number of 2800 degree-days or 67200 degc.h having, say, a 40 m^2 (for example) solar collector, then we have:

Table (1.1)

Month	degc.h month A	Space heat requir. 0.25xA KWh B	Horiz. total radiation KWh/m^2 C	Unit collection cx1.5x0.30 KWh/m^2 D	Total collection Dx40 m^2 KWh E	Solar contrib. E but not more than B KWh F
Jan	10560	2640	18.3	8.235	329.4	329.4
Feb.	9600	2400	30.9	13.905	556.2	556.2
Mar.	9120	2280	60.6	27.270	1090.8	1090.8
Apr.	6840	1710	111.9	50.355	2014.2	1710.0
May	4728	1182	123.2	55.440	2217.6	1182.0
Jun.	-	-	150.4	67.680	2707.2	-
Jul.	-	-	140.4	63.180	2527.2	-
Aug.	-	-	125.7	56.565	2262.6	-
Sep.	3096	774	85.9	38.655	1546.2	774.0
Oct.	5352	1388	47.6	21.420	856.8	856.8
Nov.	8064	2016	23.7	10.665	426.6	426.6
Dec.	9840	2460	14.4	6.480	259.2	259.2
Total	67200	16800	933.0	419.850	16794.0	7185.0

Table (1.2): Displays solar contribution and utilization rate for various collector sizes.

All Values in KWh	Heating requir. B	Unit collection D	$10m^2$ total D x 10	net	$20m^2$ total D x 20	net
Jan.	2640	8.235	82.35	82.35	164.7	164.7
Feb.	2400	13.905	139.05	139.05	278.10	278.1
Mar.	2280	27.270	272.70	272.70	545.4	545.4
Apr.	1710	50.355	503.55	503.55	1007.1	1007.1
May	1182	55.440	554.40	554.40	1108.8	1108.8
Jun.	-	67.680	676.80	-	1353.6	-
Jul.	-	63.180	631.80	-	1163.6	-
Aug.	-	56.565	565.65	-	1131.3	-
Sep.	774	38.655	386.55	386.55	773.10	773.10
Oct.	1388	21.420	214.20	214.20	428.40	428.40
Nov.	2016	10.665	106.65	106.65	213.30	213.30
Dec.	2460	6.470	64.80	64.80	129.60	129.60
Total	16800	419.850	4198.50	2324.25	8397.00	4648.50
Utiliz.rate				0.5536		0.5536

Table (1.2) (Continue)

Month	40 m^2 total	net	60 m^2 total	net	80 m^2 total	net
Jan.	329.4	329.4	494.1	494.1	658.8	658.8
Feb.	556.2	556.2	834.3	834.3	1112.4	1112.4
Mar.	1090.8	1090.8	1636.2	1636.2	2181.6	2181.6
Apr.	2014.2	1710.0	3021.3	1710.0	4028.4	1710.0
May	2217.6	1182.0	3326.4	1182.0	4435.2	1182.0
June.	2707.2	-	4060.8	-	5414.2	-
Jul.	2527.2	-	3790.8	-	5054.4	-
Aug.	2262.6	-	3393.9	-	4525.2	-
Sep.	1546.2	774.0	2319.3	774.0	3092.4	774.0
Oct.	856.8	856.8	1286.2	1286.2	1713.6	1388.0
Nov.	426.6	426.6	639.9	639.9	1253.2	1253.2
Dec.	259.2	259.2	388.8	388.8	518.4	518.4
Total	16794	7185.0	25191.06	8945.5	33588	10778.4
Utiliz. rate		0.4278		0.3551		0.3209

Table (1.3) reveals the costs of the auxiliary heating system needed at each collector size and the corresponding total costs for the two different capital costs of the solar collector (£ 15/m^2 and £ 10/m^2) using various types of fuels.

Table (1.3): (Expected life time of the auxiliary heating system is 5 years).
(a) Gas (£ 0.0073KWh x 5 = 0.0365).

Collector area m^2	Auxiliary heat per year KWh	Costs of auxil. heat = £5x0.0073 KWh	Cap.cost (£ 10/m^2)	T. cost ($\frac{£10}{m^2}$)	C.cost (£15/m^2)	T. cost ($\frac{£15}{m^2}$)
0	16800.00	613.20	0	613.20	0	613.20
10	14475.75*	528.36	100	628.36	150	679.36
20	12151.50	443.53	200	643.53	300	743.53
40	9615.00	350.95	400	750.95	600	950.95
60	7854.50	386.69	600	886.69	900	1186.69
80	6021.60	219.79	800	1019.79	1200	1419.79

* Auxiliary heating/year at 10m^2 solar collector is equal to (heat requirement(16800))-(net solar contribution at 10 m^2 (2324.25))=14475.75 KWh.

(b) Paraffin oil (£ 0.0092 KWh x 5 = 0.046)

0	16800.0	772.80	0	772.8	0	772.8
10	14475.75	665.88	100	765.88	150	815.88
20	12151.5	558.97	200	758.97	300	858.97
40	9615.0	442.29	400	842.29	600	1042.29
60	7854.5	361.31	600	961.32	900	1261.31
80	6021.6	276.99	800	1076.99	1200	1476.99

(c) Fuel oil (£ 0.0068/KWh x 5 = 0.0340)

0	16800.0	571.2	0	571.2	0	571.2
10	14475.75	492.18	100	592.18	150	642.18
20	12151.5	413.15	200	613.15	300	713.15
40	9615.0	326.91	400	726.91	600	926.91
60	7854.5	267.05	600	867.05	900	1167.05
80	6021.6	204.73	800	1004.73	1200	1404.73

(d) House coal (£ 0.0051/KWh x 5 = 0.0255)

0	16800.0	428.4**	0	428.4	0	426.4
10	14475.75	369.13	100	469.13	150	519.13
20	12151.5	309.86	200	509.86	300	609.86
40	9615.0	245.18	400	645.18	600	845.18
60	7854.5	200.29	600	800.29	900	1100.29
80	6021.6	153.55	800	953.55	1200	1353.55

** Costs of auxiliary heat along 5 years using house coal = 16800 x 0.0255 = £ 428.4.

(e) Anthracite (£ 0.0049/KWh x 5 = 0.0245)

0	16800.0	411.6	0	411.6	0	411.6
10	14475.0	354.66	100	454.66***	150	504.66
20	12151.5	297.71	200	497.71	300	597.71
40	9615.0	235.57	400	635.57	600	835.57
60	7854.5	192.44	600	792.44	900	1092.44
80	6021.6	147.53	800	947.53	1200	1347.53

*** Total costs along the 5 years of the heating system using £ 10/m^2 solar collector = 354.66 + 100 = £ 454.66.

(f) Coke (£ 0.0057/Kwh x 5 = 0.0285)

0	16800.0	478.8	0	478.8	0	478.8
10	14475.75	412.56	100	512.56	150	562.56
20	12151.5	346.32	200	546.32	300	646.32
40	9615.0	274.03	400	674.03	600	874.03
60	7854.5	223.85	600	823.85	900	1123.85
80	6021.6	171.62	800	971.62	1200	1371.62

The computations are repeated and executed for 10 years and 15 years as life times of the auxiliary heating system.

All prevous results are also deduced when the specific heat loss rate = 0.5 & 1.0 KW/°C at the prementioned constraints of different solar collector areas, various types of fuel & capital costs and 5, 10 & 15 years life times.

2.5. Conclusion and Comments on the results.

The expression of total costs is used for the costs of solar collector (copital cost) plus the cost of the auxiliary heating system used to withstand the heat requirement along the expected life-time of the latter. The total costs for various solar collector areas (0, 10, 20, 40, 60 and 80 m^2) are plotted as revealed by figures 1, 2,...., 9.

Figures 1, 2 & 3 displays case 1 when the specific heat loss rate = 0.25 KW/°C, where figures 4, 5 & 6 belong the second case of 0.5 KW/°C and finally case 3 is explained by the figures 7, 8 & 9.

Case 1. Specific heat loss rate = 0.25 KW/°C.

Family of curves are drawn for each expected life-time (5, 10 & 15 years), when the capital costs has the values of £ 10/m^2 (dotted lines) and £ 15/m^2 (solid lines) and for various types of fuel.

From figure 1, we remark that:

a) The variation of the total costs against solar collector area shows that they increase with a rapid rate.

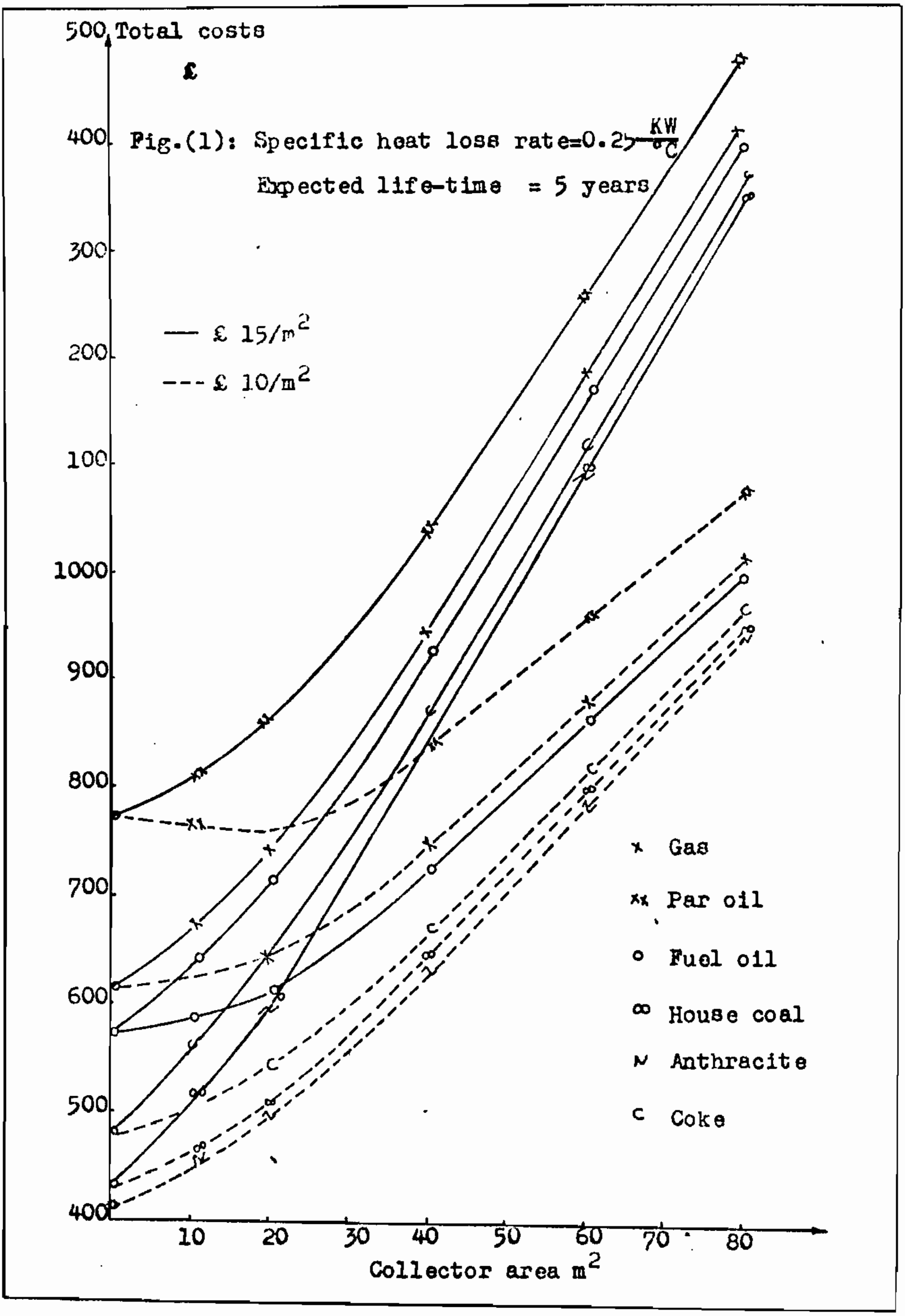


Fig.(1): Specific heat loss rate=0.25 $\frac{KW}{^{\circ}C}$

Expected life-time = 5 years

b) Paraffin oil at £ 15/m^2 leads to highest total costs compared with other types of fuel. However, anthracite at £ 10/m^2 yields the lowest total costs than various kinds of fuel taken.

c) Using the solar collector under these conditions increases the total costs along the period taken hare (5-years).

Thus, we can satisfy with the auxiliary heating system only to fulfil the heat requirement.

Going now to figure 2 (10-years), one can conclude that:

a) We have a minimum point (i.e. total cost) for all types of fuel taken but when the capital cost = £ 10/m^2. However, this point differs according to the type of fuel i.e. the optimum solar collector size is not the same as shown by the following table:

Specific heat loss rate = 0.25 KW/°C
Expected life-time = 10-years.

a- Capital cost = £ 10/m^2

Type of fuel	Optimum collector size m^2	Corresponding total costs £	Maximum collector size
Gas	26	1080.00	78
Parafin oil	30	1275.00	no max.
Fuel oil	25	1015.00	64
House coal	20	819.70	32
Anthracite	20	795.42	30
Coke	20	892.64	43

The optimum collector size is 20 m^2
The corresponding costs = £ 795.42

b- Capital cost = £ 15/m^2

Gas	20	1187.06	30
Paraffin oil	21	1417.94	50
Fuel oil	20	1126.30	24
House coal	no minimum point		no max.
Anthracite	no minimum point		" "
Coke	no minimum point		" "

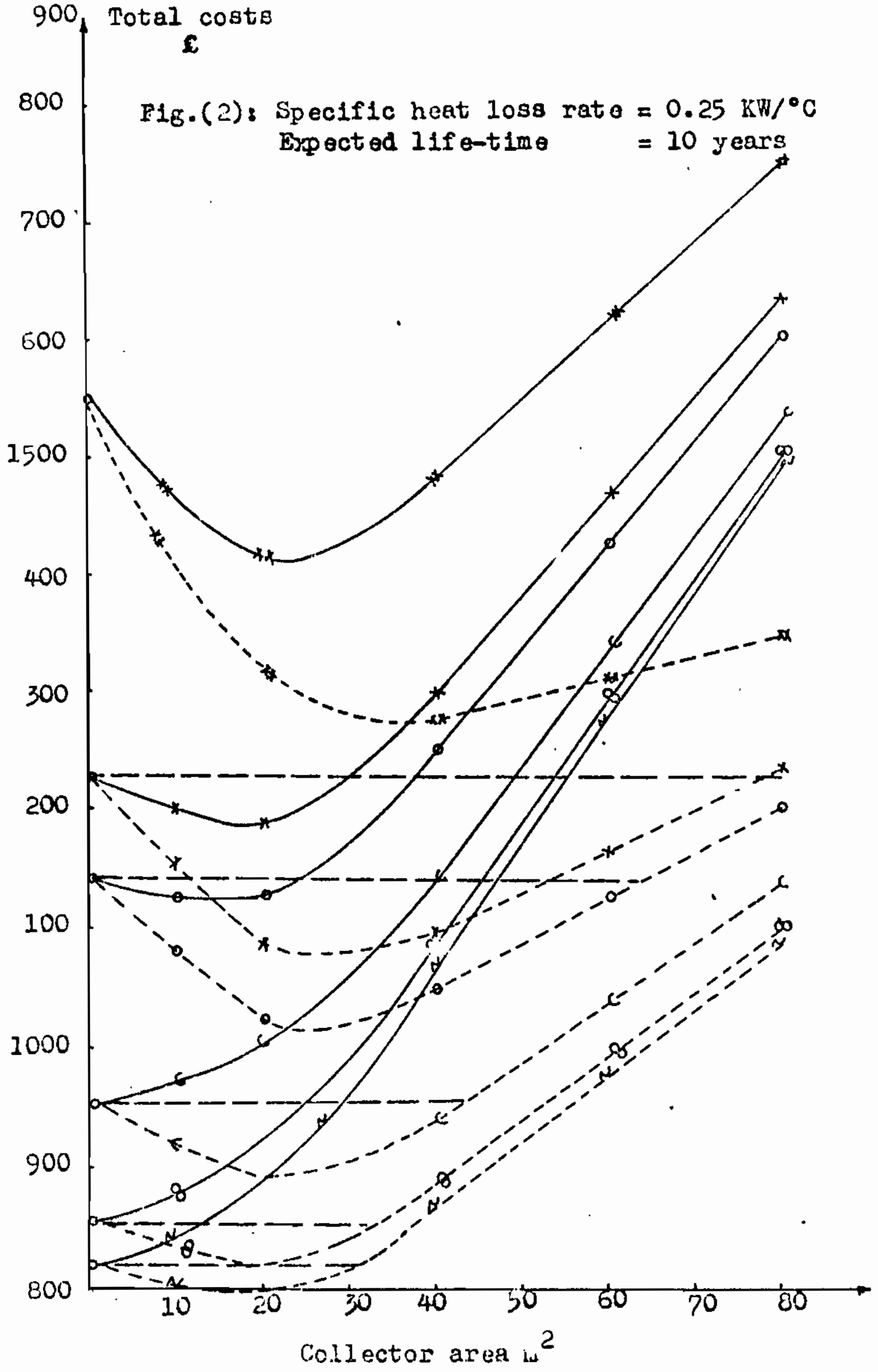


Fig.(2): Specific heat loss rate = 0.25 KW/°C
Expected life-time = 10 years

The maximum collector sizes beyond which the total cost (using solar collector) increases than the costs of the conventional fuel for different parameters are tabulated as displayed in the preceding table.

b) Using House coal, anthracite, and coke as fuels, the total costs have <u>no minimum</u> and increase rapidly versus the solar collector area.

c) Paraffin oil has the highest total costs characteristic on using £ 15/m^2 as a capital cost. However, anthracite gives the minimum costs when the capital cost = £ 10/m^2. Its minimum total costs yields 20 m^2 as an optimum solar collector.

Regarding Fig. 3 (15-years), we have:

a) Paraffin oil has the greatest total costs at £ 15/m^2 with respect to other types of fuel. However, anthracite has the lowest characteristic when the capital cost equals to £ 10/m^2.

b) The optimum collector sizes for various parameters satisfying the constraint of minimum total cost are summarized as follows:

Specific heat loss rate = 0.25 KW/°C
Expected life-time = 15 years.

a- Capital cost = £ 10/m^2

Type of fuel	Optimum collector size m^2	Corresponding costs £	Maximum collector size m^2
Gas	40	1450	no max.
Paraffin oil	no minimum point		"
Fuel oil	36	1375	"
House coal	27	1110	87
Anthracite	26	1080	77
Coke	20	1225	no max.

The optimum collector size is 26 m^2
The corresponding costs £ 1080

b- Capital cost = £ 15/m^2

Gas	26	1615	76
Paraffin oil	35	1925	no max.
Fuel oil	27	1525	62
House coal	20	1225	33
Anthractie	20	1190	31
Coke	23	1330	42

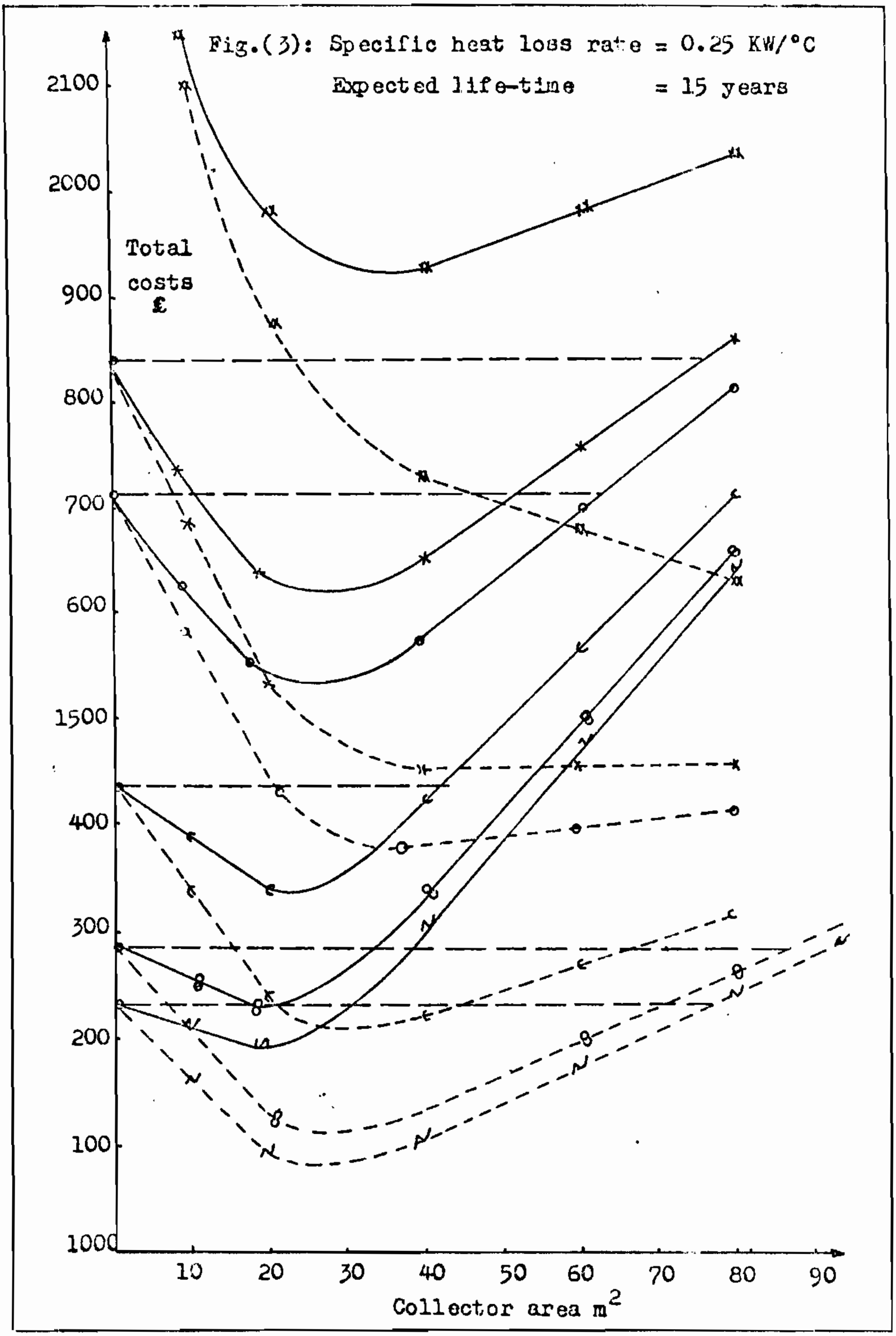


Fig.(3): Specific heat loss rate = 0.25 KW/°C
Expected life-time = 15 years

The optimum collector size is 20 m^2
The corresponding costs £ 1190

Case 2. Specific heat loss rate = 0.5 KW/°C.

When we study figure 4. (Expected life-time is taken 5-years), then we can conclude that:

a) Paraffin oil has greater total costs for all collector sizes than other types. This occurs when the capital cost has £ 15/m^2 of solar collector, although anthracite has the lowest characteristic.

b) All the curves for different parameters have increasingly characteristics sxcept for paraffin oil at £ 10/m^2 which has a minimum point of 40 m^2 as a solar collector size with corresponding costs of £ 1510 total costs.

Investigating Fig. 5 (10 years), the optimum collector size for various parameters are tabulated as follows:

a- Capital cost £ 10/m^2

Type of fuel	Optimum collector size m^2	Corresponding total costs £	Maximum collector size m^2
Gas	60	2160	no max.
Par. oil	71	2540	no max.
Fuel oil	50	2040	no max.
House coal	40	1635	66
Anthracite	40	1585	60
Coke	43	1785	82

The optimum collector size is 40 m^2
The corresponding total costs is £ 1585

b- Capital cost = £ 15/m^2

Gas	34	2400	58
Par. oil	55	2860	98
Fuel oil	33	2240	47
House coal	no minimum point		no max.
Anthracite	no minimum point		"
Coke	no minimum point		"

The optimum collector size = 33 m^2
The corresponding total costs = £ 2240

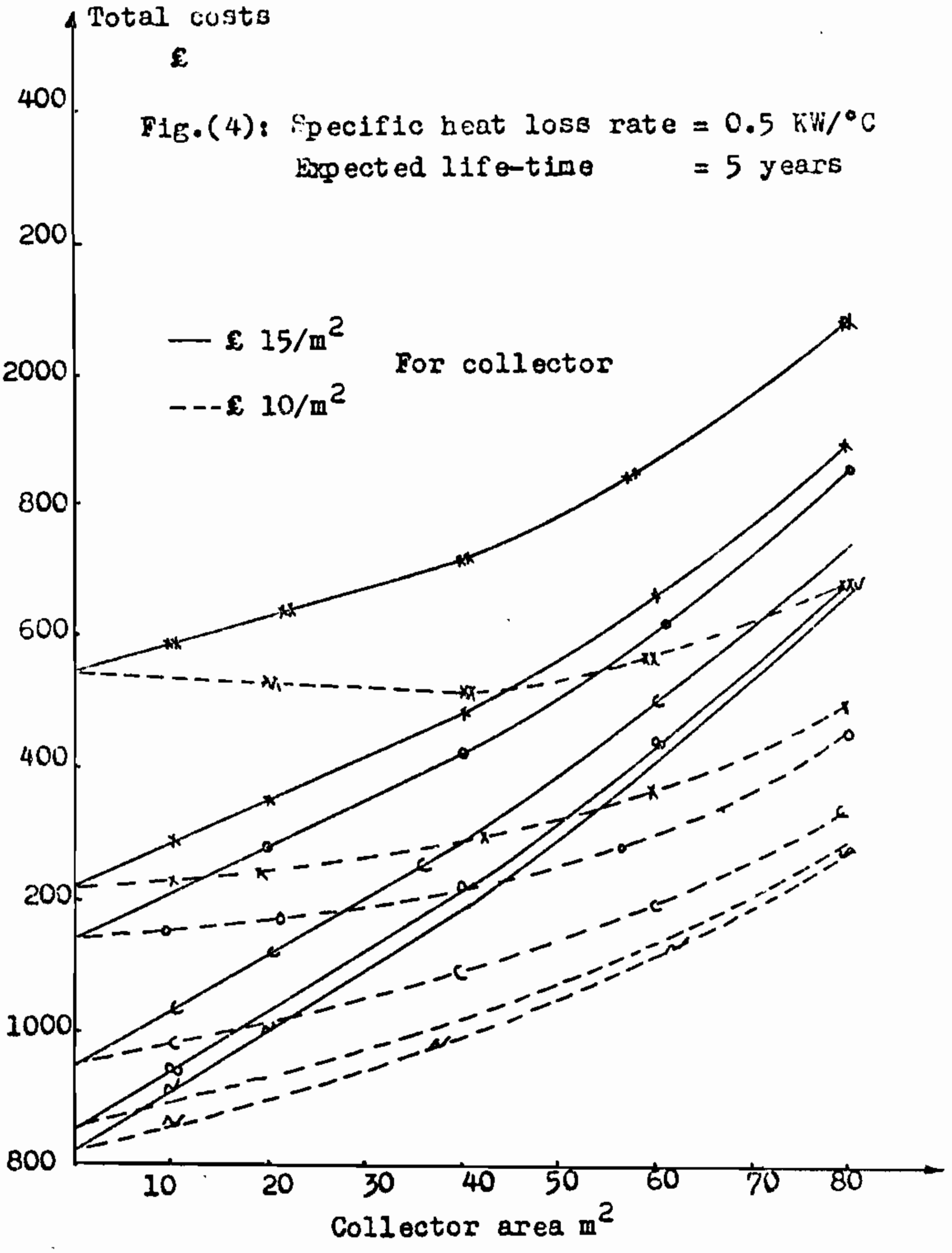


Fig.(4): Specific heat loss rate = 0.5 KW/°C
Expected life-time = 5 years

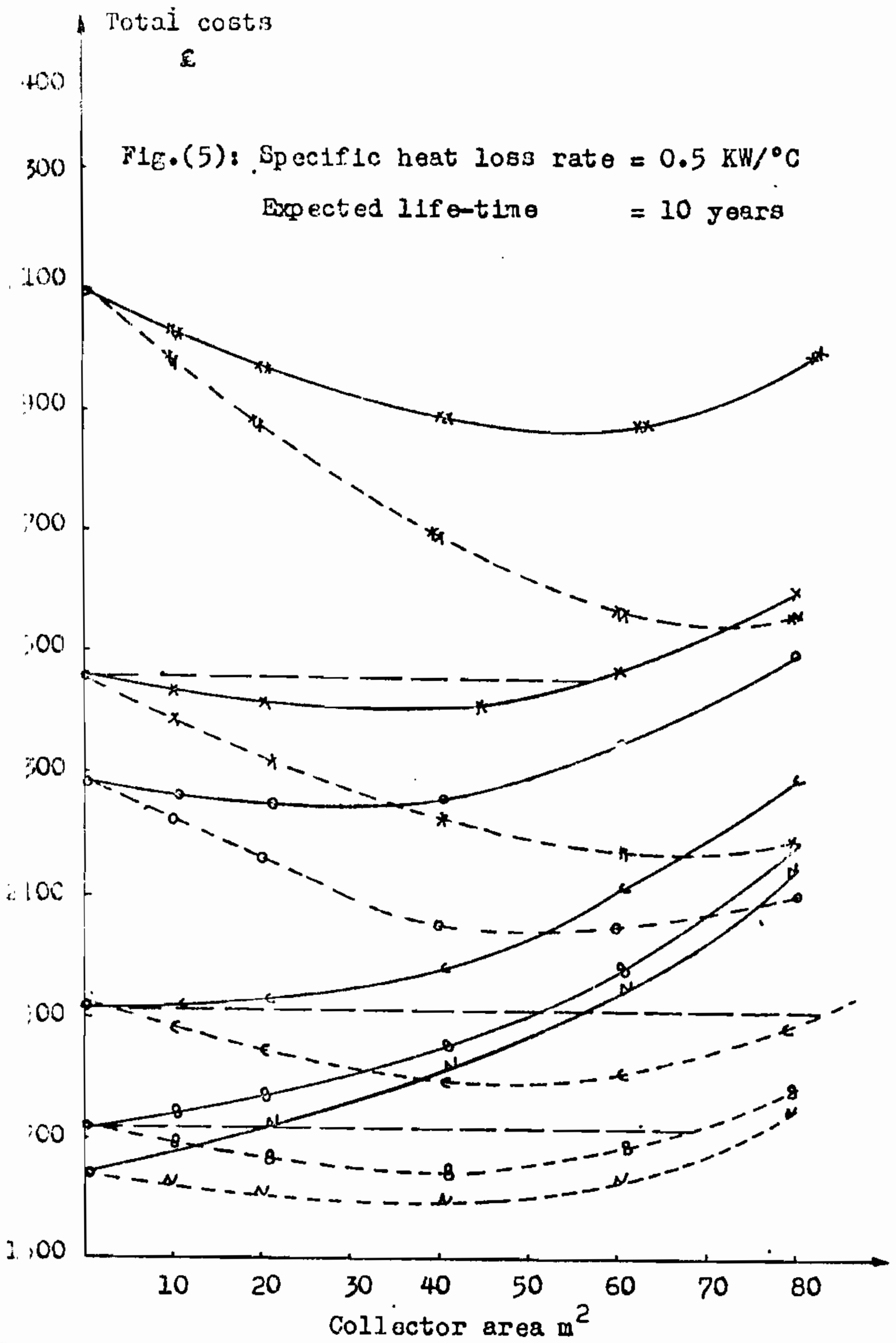


Fig.(5): Specific heat loss rate = 0.5 KW/°C
Expected life-time = 10 years

On studying Fig. 6(15 years), we summarize the optimum collector size and the maximum collector size beyond which the total costs is greater than that of the conventional one:

a- Capital cost = £ 10/m^2

Type of fuel	Optimum collector size m^2	Corresponding total costs £	Maximum collector size m^2
Gas	no minimum point		no max.
Par. oil	60	3885	no max.
Fuel oil	no minimum point		no max.
House coal	50	2210	no max.
Anthracite	53	2160	113
Coke	60	2410	no max.

The optimum collector size is 53 m^2

b- Capital cost = £ 15/m^2

Gas	49	3225	no max.
Par. oil	60	3885	no max.
Fuel oil	47	3040	no max.
House coal	40	2460	65
Anthracite	40	2380	60
Coke	40	2675	83

The optimum collector size is 40 m^2
The corresponding total costs = £ 2380

Case 3: Specific heat loss rate = 1.0 KW/°C

With respect to Fig. 7(5 years), we remark that all the characteristics are linearly varied and have no minimum point as in the preceding two cases. Moreover, these curves are increasingly functions i.e. on using larger size of solar collector, the total costs increase, except for paraffin oil (when capital cost = £ 10/m^2), it has decreasingly function.

Researching for Fig. 8(10 years) we notice that the variations are linear but with increasingly, decreasingly and constant functions as shown.

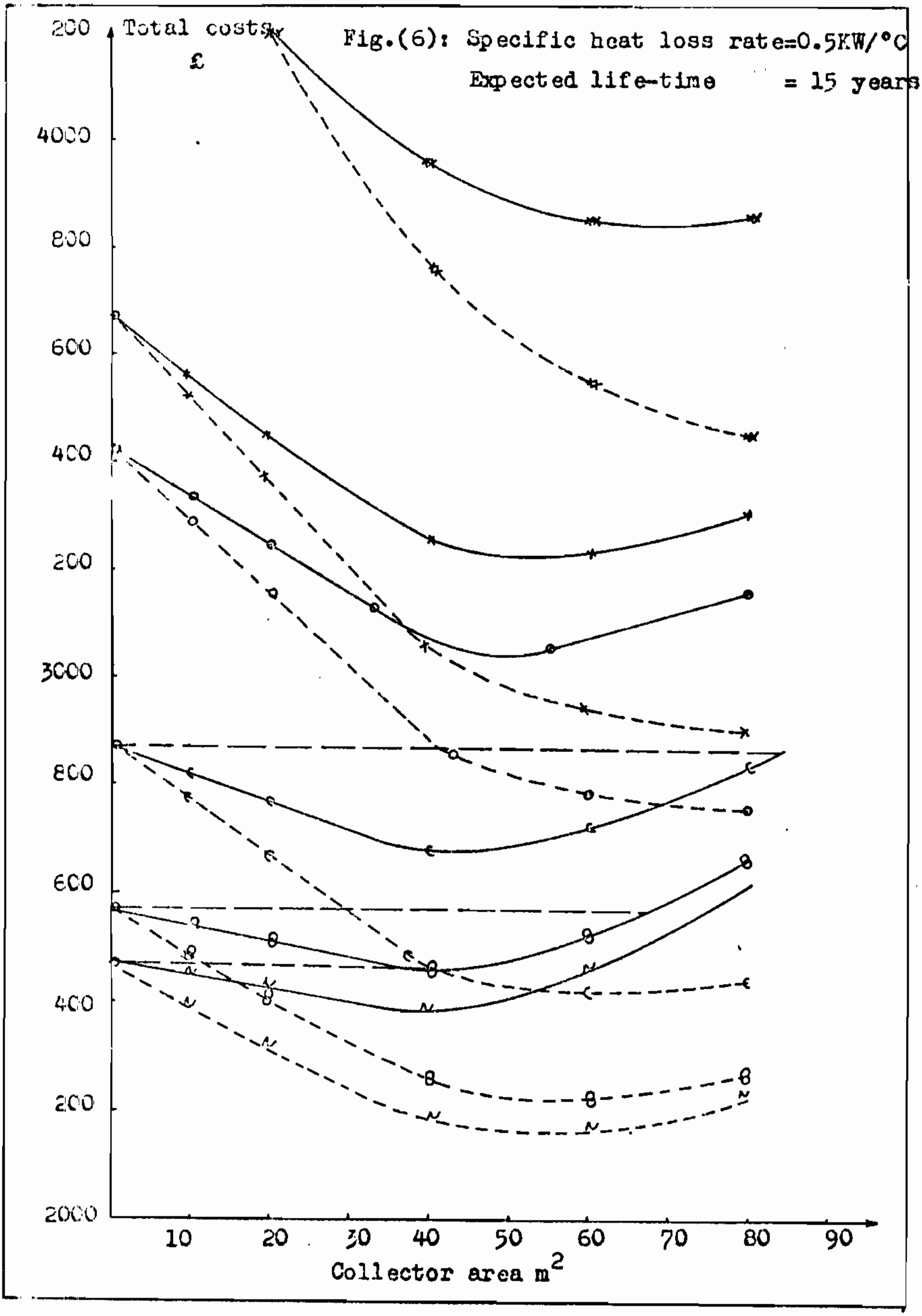


Fig.(6): Specific heat loss rate=0.5KW/°C
Expected life-time = 15 years

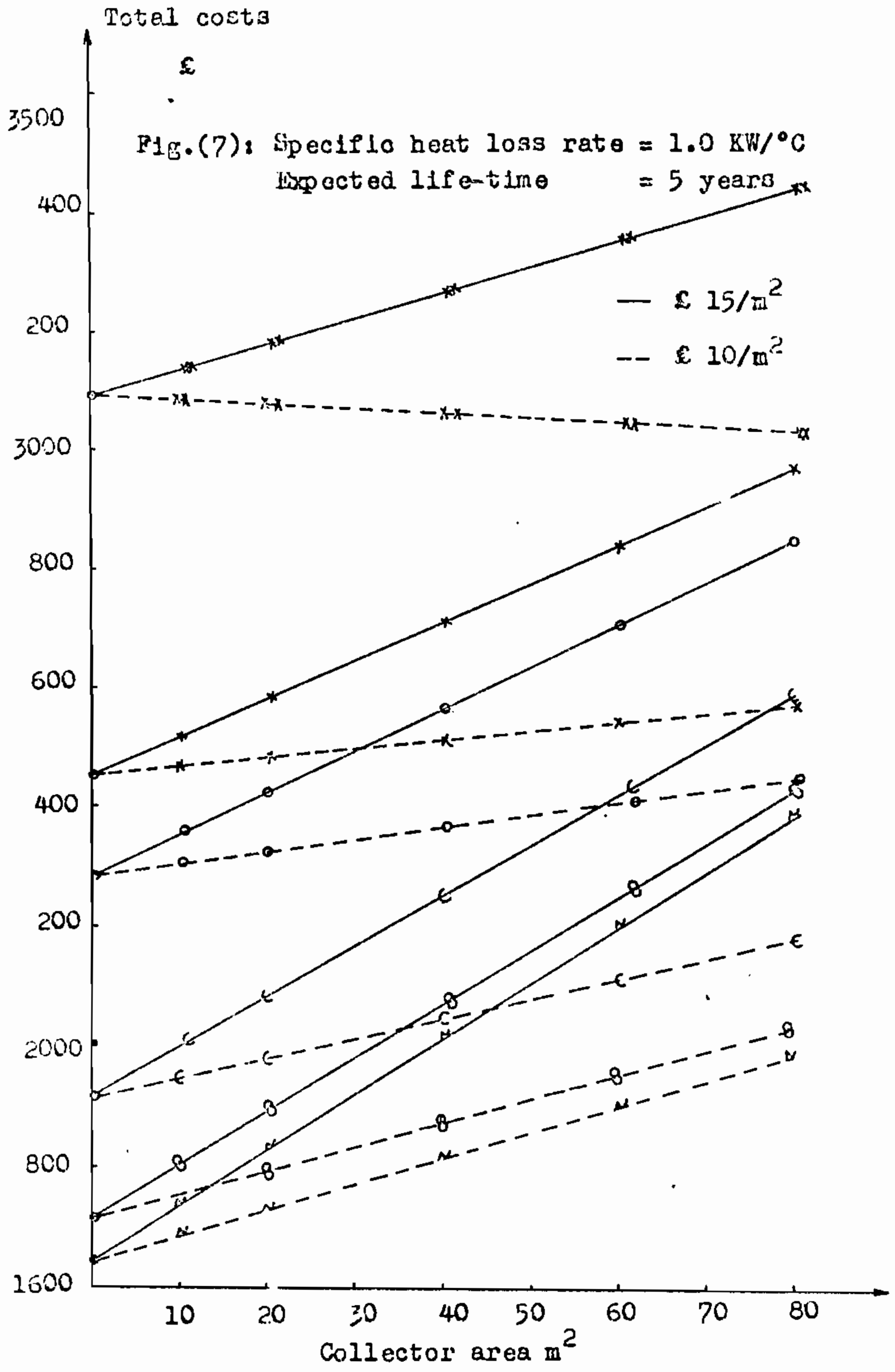


Fig.(7): Specific heat loss rate = 1.0 KW/°C
Expected life-time = 5 years

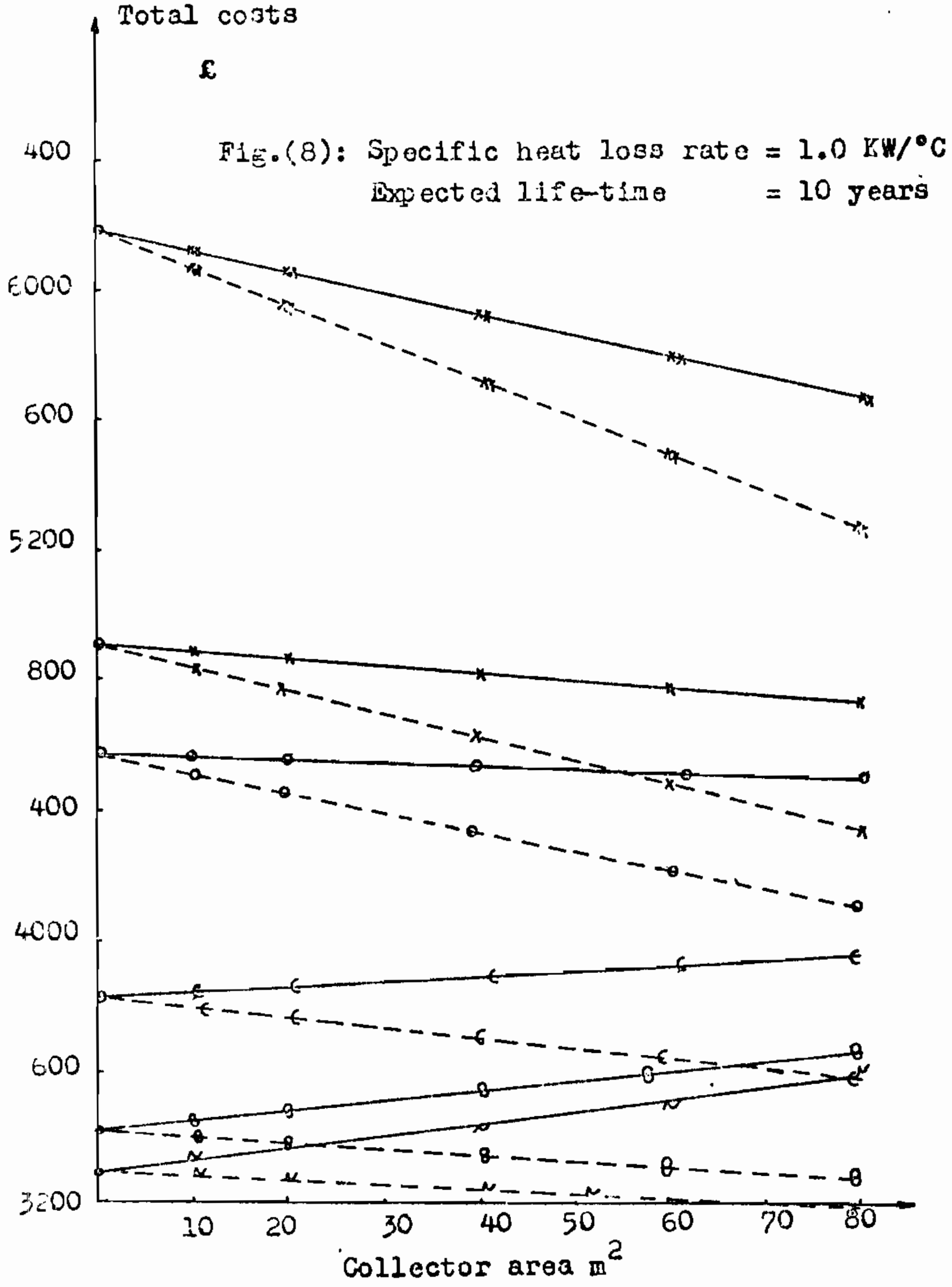


Fig.(8): Specific heat loss rate = 1.0 KW/°C
Expected life-time = 10 years

Paraffin oil is the more expensive type of fuel compared with other types under study, however, anthracite is the cheapest.

The fuel oil has a nearly constant characteristic i.e. it has the same total costs on using different sizes of solar collector.

Eventually, from Fig. 9, we remark that the corresponding family curves vary linearly against various collector sizes but with reducingly characteristics i.e. the total costs decrease on using larger solar collector size in the range chosen for the collector areas. This phenomenon occurs for all types of fuel.

2.6. Figure of merit (FM)

It is defined as $\dfrac{\text{Energy saved by the install. in 10 years}}{\text{Extra cost of install. over conven one}}$

It has been suggested that the system will be competitive i (FM) reaches a value of 1.

Cose 1. Specific heat loss rate = 0.25 KW/°C

a- Gas
(£ 0.0073/KWh 10 years = £ 0.073/KWh)

Collector size m^2	Net solar contribut (KWh)G	Energy saved Gx0.073=H	Extra costs £10/m^2 I	FM (£10/m^2) H/I	Extra costs £15/m^2 I′	FM (£15/m^2) m^2 H/I′
10	2324.25	169.67	100	1.69	150	1.13
20	4648.50	339.34	200	1.69	300	1.13
40	7185.00	524.51	400	1.31	600	0.87
60	8945.50	653.02	600	1.09	900	0.73
80	10778.40	786.82	800	0.98	1200	0.66

b- Paraffin oil
(£ 0.0092/KWh x 10 years = £ 0.092/KWh)

10	2324.25	213.83	100	2.14	150	1.43
20	4648.50	427.66	200	2.14	300	1.43
40	7185.00	661.02	400	1.65	600	1.10
60	8945.50	822.99	600	1.37	900	0.91
80	10778.40	991.61	800	1.24	1200	0.83

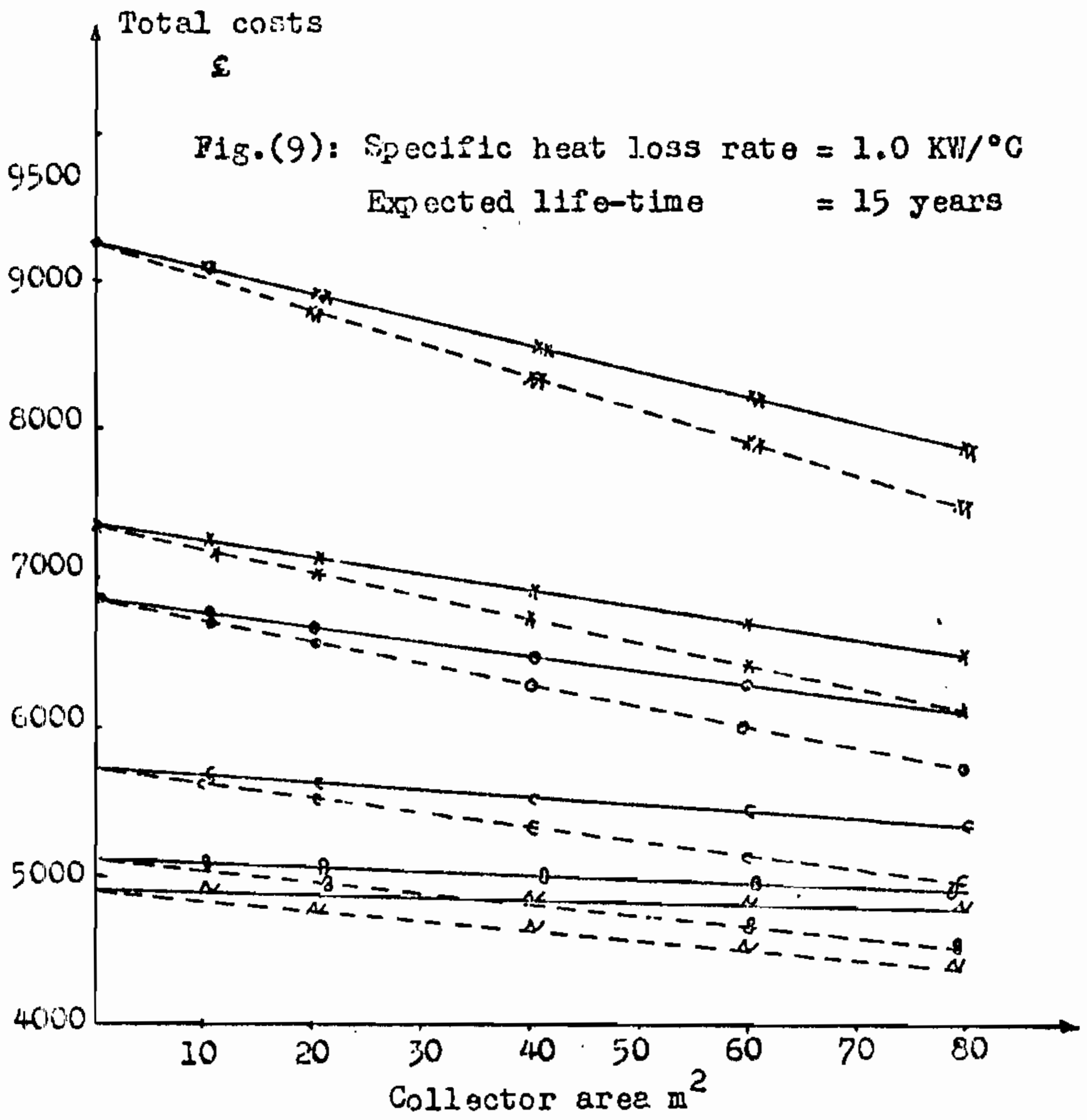


Fig.(9): Specific heat loss rate = 1.0 KW/°C
Expected life-time = 15 years

c- Fuel oil
(£ 0.0068/KWh x 10 years = £ 0.068/KWh).

10	2324.25	158.05	100	1.58	150	1.05
20	4648.50	316.09	200	1.58	300	1.05
40	7185.00	488.58	400	1.22	600	0.81
60	8945.50	608.29	600	1.01	900	0.68
80	10778.40	732.93	800	0.92	1200	0.61

d- House coal
(£ 0.0051/KWh x 10 years = £ 0.051/KWh).

10	2324.25	118.54	100	1.19	150	0.79
20	4648.50	237.07	200	1.19	300	0.79
40	7185.00	366.44	400	0.92	600	0.61
60	8945.50	456.22	600	0.76	900	0.51
80	10778.40	549.69	800	0.69	1200	0.46

e- Anthracite
(£ 0.0049/KWh x 10 years = £ 0.049/KWh)

10	2324.25	213.89	100	1.14	150	0.76
20	4648.50	227.78	200	1.14	300	0.76
40	7185.00	352.07	400	0.88	600	0.59
60	8945.50	438.33	600	0.73	900	0.49
80	10778.40	528.14	800	0.66	1200	0.44

f- Coke
(£ 0.0057/KWh x 10 years = £ 0.057/KWh).

10	2324.25	132.48	100	1.32	150	0.88
20	4648.50	264.96	200	1.32	300	0.88
40	7185.00	409.55	400	1.02	600	0.68
60	2945.50	509.89	600	0.85	900	0.57
80	10778.40	614.37	800	0.77	1200	0.51

Case 2. Specific heat loss rate = 0.5 KW/°C

a- Gas
(£ 0.0073/KWh x 10 years = £ 0.073/KWh)

Collector size m^2	Net solar contribut G	Energy saved $G \times 0.073 = H$	Extra costs (£10/m^2) I	FM (£10/m^2) H/I	Extra costs (£15/m^2) I´	FM (£15/m^2) H/I´
10	2324.25	169.67	100	1.69	150	1.13
20	4648.50	339.34	200	1.69	300	1.13
40	9297.00	678.68	400	1.69	600	1.13
60	12212.80	891.53	600	1.49	900	0.99
80	14370.00	1049.01	800	1.31	1200	0.87

b- Paraffin oil
(£ 0.0092/KWh x 10 years = £ 0.092/KWh)

10	2324.25	213.83	100	2.14	150	1.43
20	4648.50	427.66	200	2.14	300	1.43
40	9297.00	855.32	400	2.14	600	1.43
60	12212.80	1123.58	600	1.87	900	1.25
80	14370.00	1322.04	800	1.65	1200	1.10

c- Fuel oil
(£ 0.0068/KWh x 10 years = £ 0.068/KWh)

10	2324.25	158.05	100	1.58	150	1.05
20	4648.50	316.09	200	1.58	300	1.05
40	9297.00	632.19	400	1.58	600	1.05
60	12212.80	830.47	600	1.38	900	0.92
80	14370.00	977.16	800	1.22	1200	0.81

d- House coal
(£ 0.0051/KWh x 10 years = £ 0.051/KWh)

10	2324.25	118.54	100	1.19	150	0.79
20	4648.50	237.07	200	1.19	300	0.79
40	9297.00	474.15	400	1.19	600	0.79
60	12212.80	622.85	600	1.04	900	0.69
80	14370.00	732.87	800	0.92	1200	0.61

e- Anthracite
(£ 0.0049/KWh x 10 years = £ 0.049/KWh)

10	2324.25	113.89	100	1.14	150	0.76
20	4648.50	227.78	200	1.14	300	0.76
40	9297.00	455.55	400	1.14	600	0.76
60	12212.80	598.43	600	0.99	900	0.66
80	14370.00	704.13	800	0.88	1200	0.59

f- Coke
(£ 0.0057/KWh x 10 years = £ 0.057/KWh)

10	2324.25	132.48	100	1.32	150	0.88
20	4648.50	264.96	200	1.32	300	0.88
40	9297.00	529.93	400	1.32	600	0.88
60	12212.80	696.13	600	1.16	900	0.77
80	14370.00	819.09	800	1.02	1200	0.68

Case 3. Specific heat loss rate = 1.0 KW/°C

a- Gas
(£ 0.0073/KWh x 10 years = £ 0.073/KWh)

10	2324.25	169.67	100	1.69	150	1.13
20	4648.50	339.34	200	1.69	300	1.13
40	9297.00	678.68	400	1.69	600	1.13
60	13945.50	1018.02	600	1.69	900	1.13
80	18594.00	1357.36	800	1.69	1200	1.13

b- Paraffin oil
(£ 0.0092/KWh x 10 years = £ 0.092/KWh)

10	2324.25	213.83	100	2.14	150	1.43
20	4648.50	427.66	200	2.14	300	1.43
40	9297.00	855.32	400	2.14	600	1.43
60	13945.50	1282.99	600	2.14	900	1.43
80	18594.00	1710.65	800	2.14	1200	1.43

c- Fuel oil
(£ 0.0068/KWh x 10 years = £ 0.068/KWh)

10	2324.25	158.05	100	1.58	150	1.05
20	4648.50	316.09	200	1.58	300	1.05
40	9297.00	632.19	400	1.58	600	1.05
60	13945.50	948.29	600	1.58	900	1.05
80	18594.00	1264.39	800	1.58	1200	1.05

d- House coal
(£ 0.0051/KWh x 10 years = £ 0.051/KWh)

10	2324.25	118.54	100	1.19	150	0.79
20	4648.50	237.07	200	1.19	300	0.79
40	9297.00	474.15	400	1.19	600	0.79
60	13945.50	711.22	600	1.19	900	0.79
80	18594.00	948.29	800	1.19	1200	0.79

e- Anthracite
(£ 0.0049/KWh x 10 years = £ 0.049/KWh)

10	2324.25	113.59	100	1.14	150	0.76
20	4648.50	227.78	200	1.14	300	0.76
40	9297.00	455.55	400	1.14	600	0.76
60	13945.50	683.33	600	1.14	900	0.76
80	18594.00	911.11	800	1.14	1200	0.76

f- Coke
(£ 0.0057/KWh x 10 years = £ 0.057/KWh)

10	2324.25	132.48	100	1.32	150	0.88
20	4648.50	264.96	200	1.32	300	0.88
40	9297.00	529.93	400	1.32	600	0.88
60	13945.50	794.89	600	1.32	900	0.88
80	18594.00	1059.86	800	1.32	1200	0.88

2.7. Conclusions and comments on:

Utilization rate (UR) and figure of merit (FM) curves.

I) Utilization rate (UR)

UR expresses the effective solar collected energy utilized for satisfying all or part of the heat requirement as a ratio to the total collected energy.
Fig. 10 displays the behaviour of UR against the solar collector areas at different values of specific heat loss rate. For small values of this rate, UR decreases by a non-linear relation.

As this rate increases (0.5 and 1.0 KW/°C), UR has a constant value at small collector sizes and then decreases at larger one.

When the specific heat loss rate = 1.0, UR possesses a constant value independent of solar collector areas.

II) Figure of merit (FM)

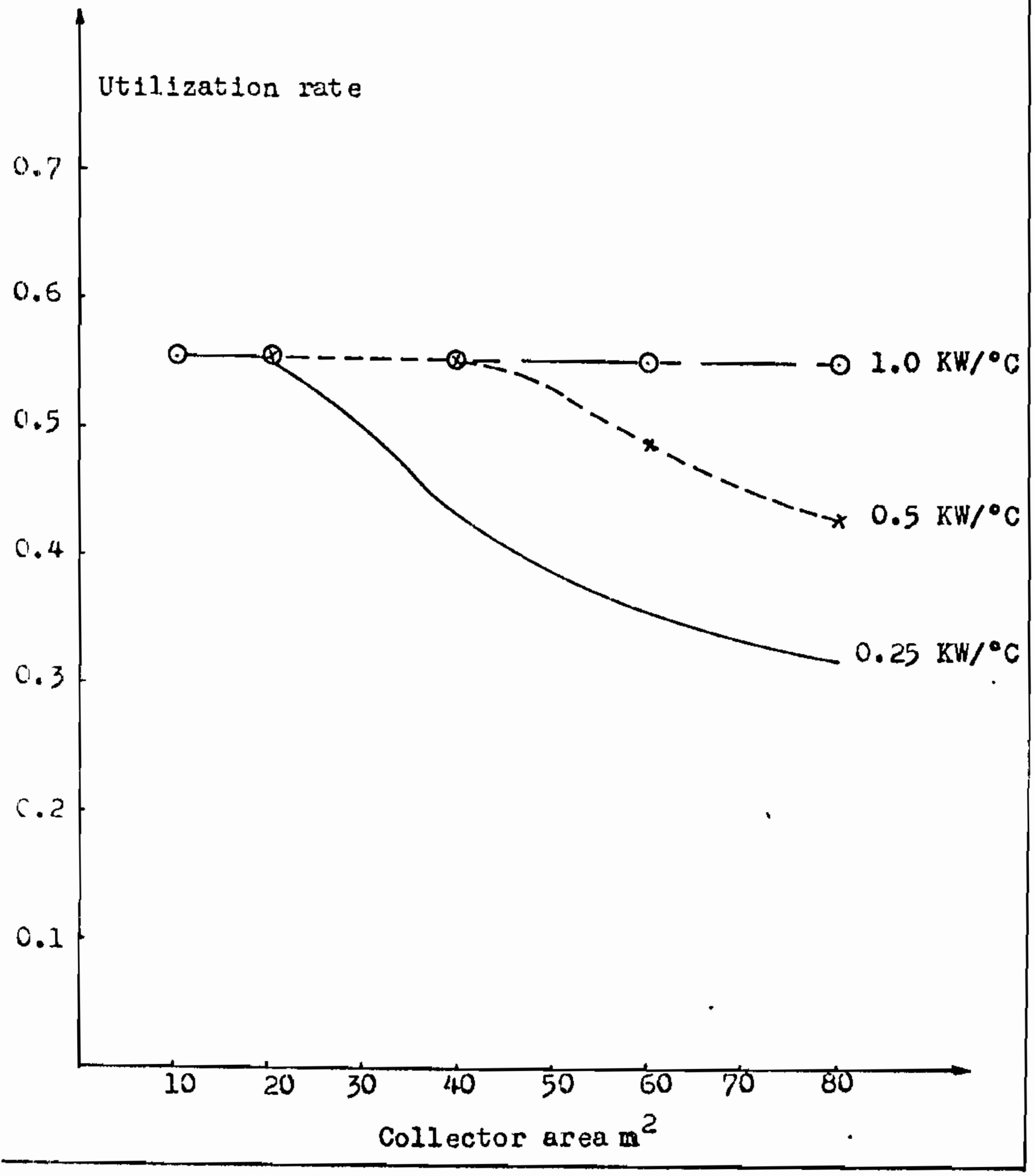
FM is plotted for 3 main cases of specific heat loss rate (0.25, (Fig. 11), 0.5(Fig.12) and 1.0(Fig. 13)).

Fig. 11 shows the variations of FM against the solar collector area for different types of fuel. We notice that the paraffin oil has the greatest ratio, however, it has the same shape as other characteristics.

This means that maximum energy is saved along the period of research on using solar collector with £ 10/m^2 as a capital cost and paraffin oil as a fuel.

On the other hand, anthracite yields minimum energy saved on using £ 15/m^2 as a capital cost.

Fig.(10): Utilization rate at different specific heat loss rate



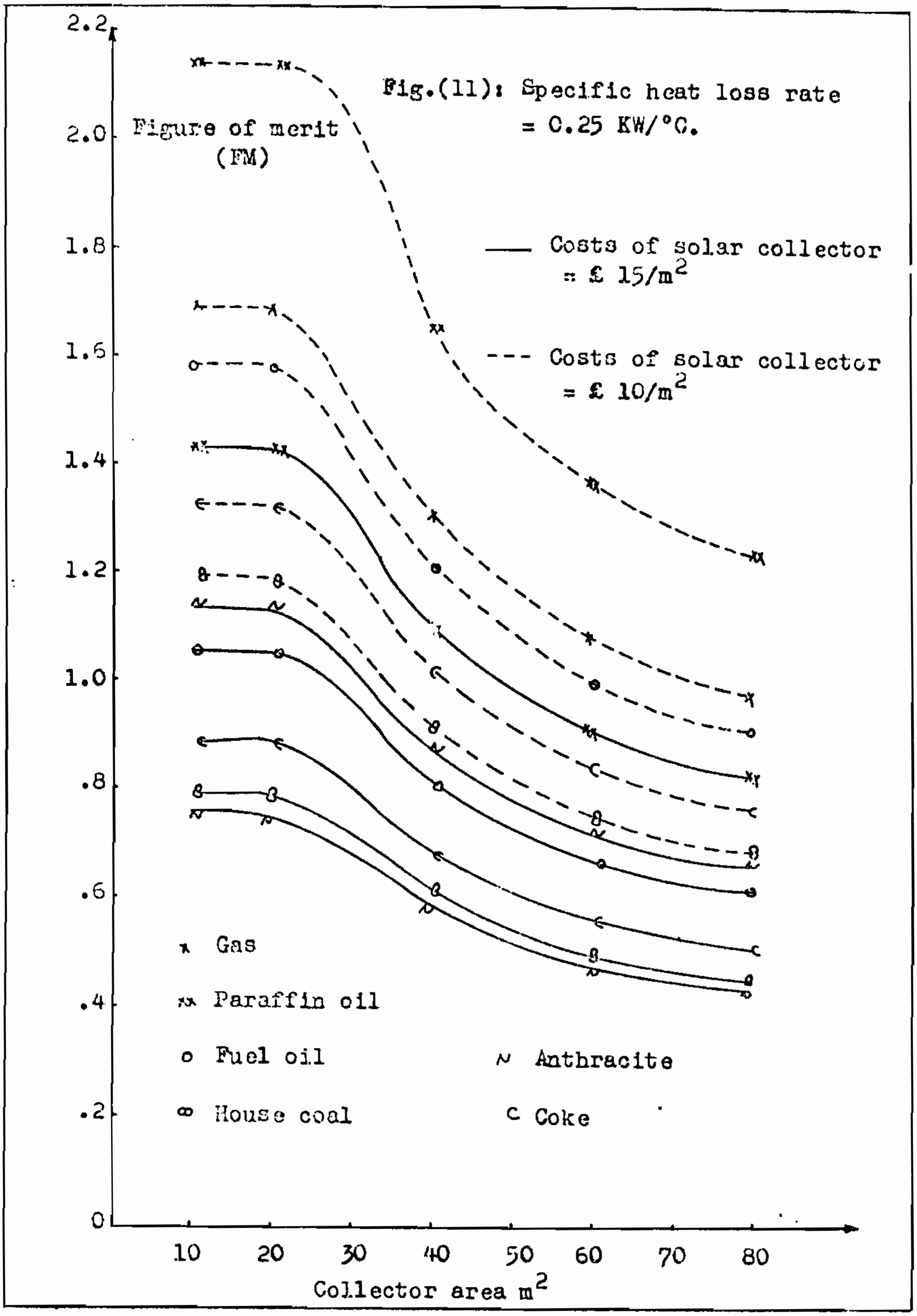


Fig.(11): Specific heat loss rate = 0.25 KW/°C.

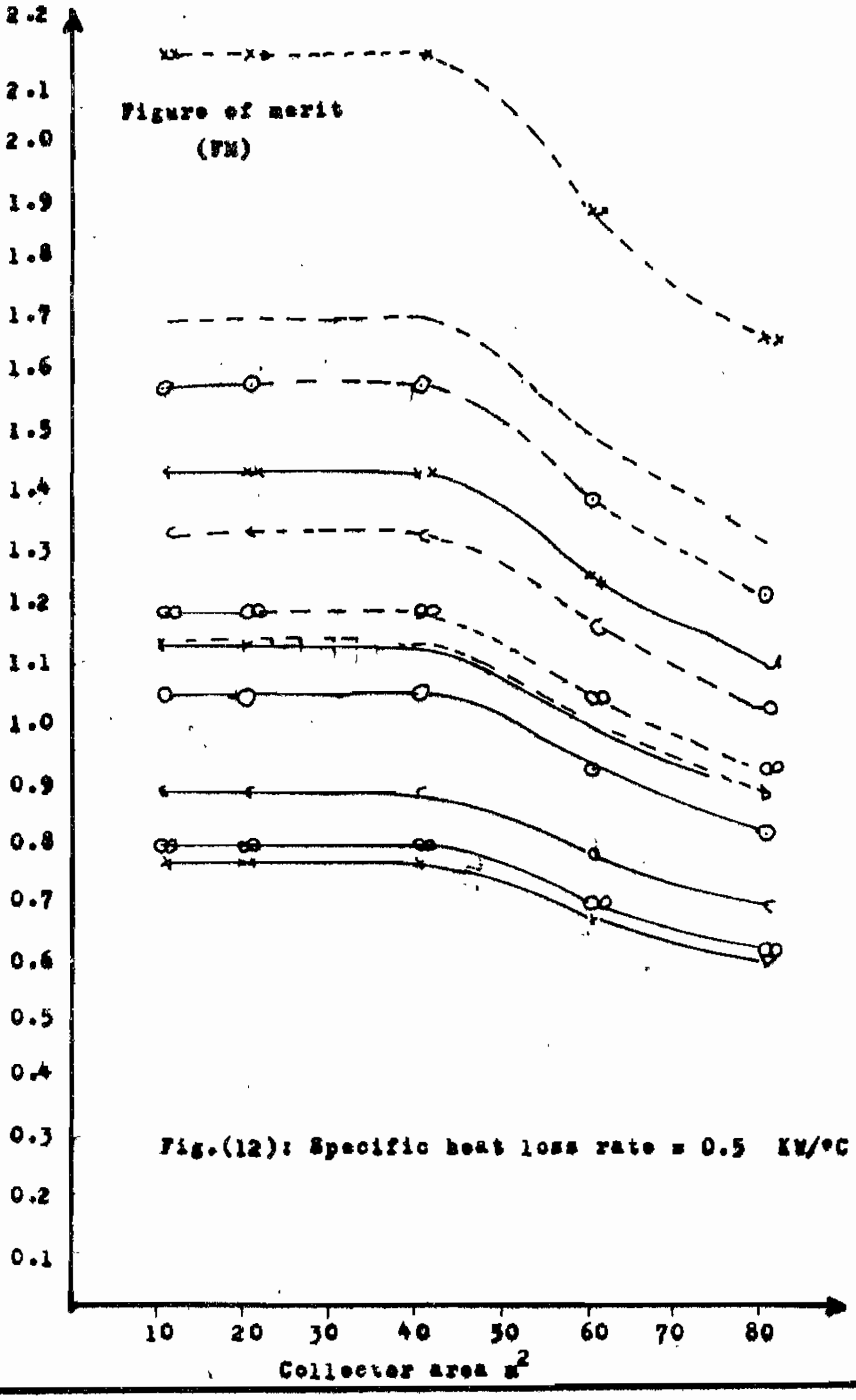


Fig.(12): Specific heat loss rate = 0.5 KW/°C

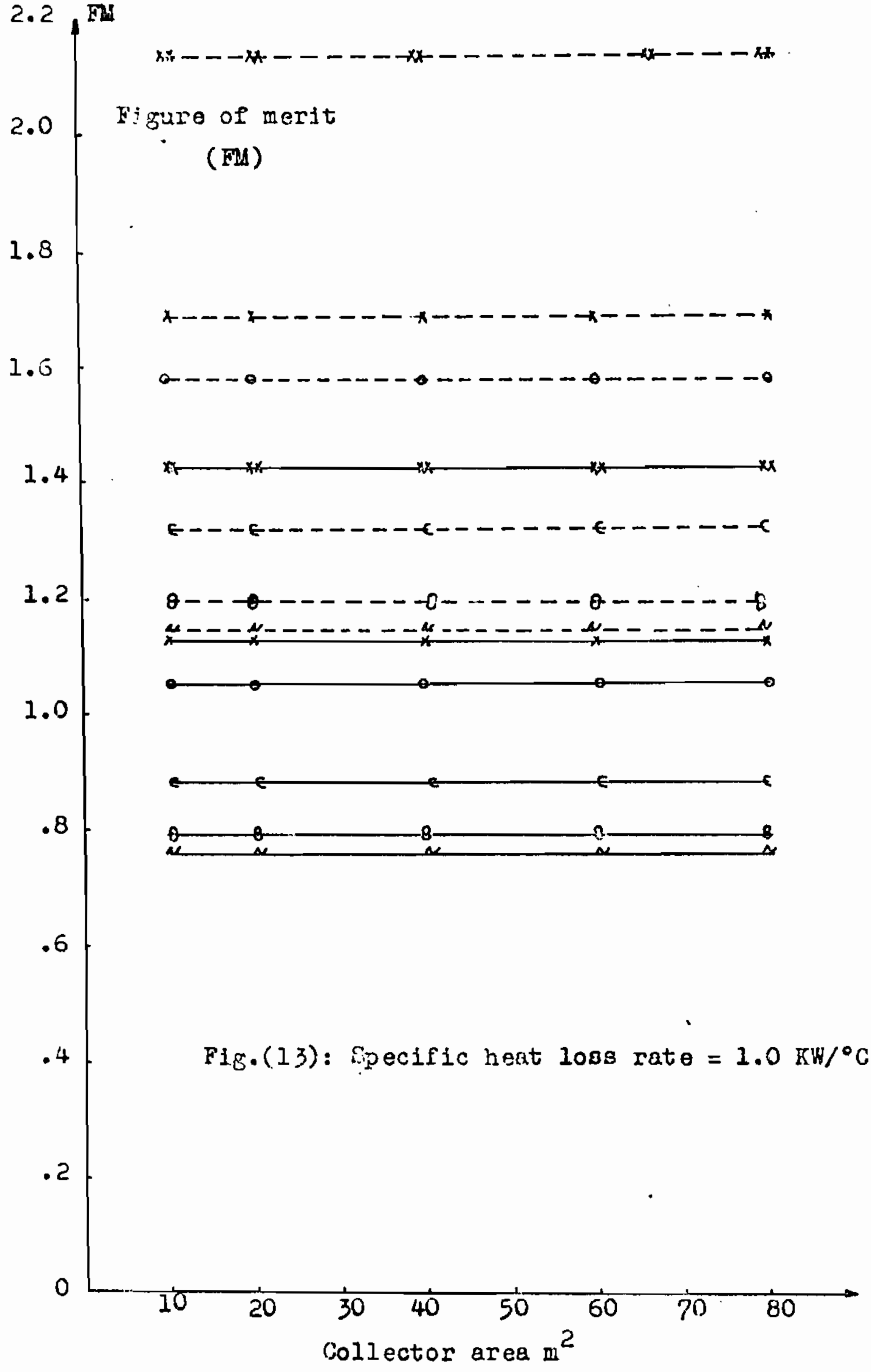


Fig.(13): Specific heat loss rate = 1.0 KW/°C

Fig. 12 reveals the variation but with specific heat loss rate = 0.5 KW/°C. Also, Paraffin oil achieves the same FM of maximum energy saved relative to the extra cost of solar collector installation. In addition, on using anthracite as a fuel, one can have minimum FM.

There is a difference between the characteristics here and that in the case of 0.25 KW/°C. It is the constancy of FM(here) along 10, 20, 30 & 40 m^2 solar collector i.e. independent of using larger sizes in this range, however, on increasing the solar collector area more than 40 m^2, FM decreases slowly with non-linear characteristic.

Fig. 13 explains the third case of specific heat loss rate of 1.0 KW/°C. We notice a very significant phenomenon which is summarized as follows:

For all types of fuel, FM has a constant but with different values independent of the size of the solar collector. Similarly, paraffin oil has a maximum FM on using £ 10/m^2 as a capital cost with respect to other types of fuel.

Again, anthracite yields minimum FM but it has a constant value against the solar collector sizes.

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