155

HEAT LOAD FOR DIESEL ENGINE-GENERATOR ROOM VENTILATION

M.M. SHAH
Member ASHRAE

INTRODUCTION

Diesel engine-generator sets are widely used for providing normal and emergency power supply in many applications. These release heat to the surroundings by the process of convection and radiation. This heat has to be removed by an appropriate ventilation system so that air temperature does not exceed the upper limit for safe operation. To design such a ventilation system requires the knowledge of heat released by the engine and generator to the engine room. Estimation of this heat load is the subject of this paper.

Once a particular engine generator set has been selected, information regarding heat added to the engine room is generally obtainable from the manufacturer. However, in many long-term projects, ventilation systems have to be designed long before the final selection can be made. A notable example is found in nuclear power plant projects in which the time lag between preliminary system design and final equipment selection through competitive bidding may be as much as five years.

At this stage, the ventilation system designer often seeks guidance from standard handbooks. An extensive search through such reference materials revealed that only the handbooks published by ASHRAE and DEMA(Diesel Engine Manufacturers' Association) provide any guidance. However, there is considerable variation between various recommendations.

In view of the foregoing, the author carried out a comparison between the heat load information published in catalogues of various manufacturers and the information provided by various handbooks. The results of that study are presented in this paper. The process of heat transfer involved and the parameters determining heat emission from engine surface are discussed. The limitations of manufacturers' data as well as the recommendations of handbooks are discussed in view of the difficulties in measurements and the complexities of the problem. The conclusion is reached that a simple generally applicable correlation between engine work output and heat release to surroundings is unlikely. Surprisingly however, it was found that for 4-stroke engines upto 1000 kw output, manufacturers' data for heat emission can be correlated in terms of engine output alone.

In engine manufacturers' catalogues as well as in many books dealing with engines, the total heat given out by the engine(and/or generator) is called "radiation." Actually, heat transfer occurs both by radiation and convection. To avoid any confusion, the use of this term has been avoided and the total heat outflow from engine surface has been called heat emission from engine. It is further stressed that all discussions here deal exclusively with water-cooled diesel engines driving air-cooled generators unless specifically noted otherwise.

HEAT TRANSFER PROCESS

M.M.Shah is a Consulting Engineer, 819 S. Mechanic, Jackson, Michigan 49203.

The engine surface loses heat to the surrounding air and surrounding surfaces by convection and radiation. Engine surface temperature is not uniform and heat is conducted through its walls in a highly complex fashion. The temperature of air around the engine is also nonuniform and the temperature of surrounding surfaces may be different from that of air. Thus the actual heat transfer process is highly complex and efforts at analyzing it exactly unlikely to be fruitful. In order to identify the important parameters affecting heat emission from engine surface, a simplified model is considered.

Engine surface temperature is assumed to be uniform at a mean value T_s and the surrounding air temperature constant and uniform at T_a, both temperatures in absolute degrees. Temperature of engine room walls is considered equal to that of air, a reasonable assumption in most cases. Both engine surface and room walls are regarded as gray. The surface area of room walls is regarded as much greater than that of the engine. The shape of the engine is generally such that heat radiated from any part of the engine is not intercepted by another part of it. For such a case, heat loss by radiation to surroundings is given by:

$$Q_{er} = \epsilon \sigma A (T_s^4 - T_a^4) \tag{1}$$

where A is the surface area of the engine, σ the Stefan-Boltzman constant, and ϵ the emissivity of the engine surface. (Derivation of this equation may be found in many textbooks and also in Chapter 2 of Ref 1.) Most of the heat absorbed by room walls is picked up by the room air.

If h_c is the convective heat transfer coefficient between ventilating air and engine surface, heat lost by convection is given by:

$$Q_{ec} = h_c A (T_s - T_a) \tag{2}$$

Thus the heat emission from the engine surface is

$$Q_{et} = Q_{er} + Q_{ec} = \sigma \epsilon A (T_s^4 - T_a^4) + h_c (T_s - T_a) \tag{3}$$

The concept of radiation heat transfer is occaisionally used. The radiation heat transfer coefficient h_r is defined by the following equation:

$$Q_{er} = h_r A (T_s - T_a) \tag{4}$$

Comparison with Eq 1 shows that

$$h_r = \sigma \epsilon (T_s^2 + T_a^2)(T_s + T_a) \tag{5}$$

Thus Eq 3 becomes

$$Q_{et} = (h_c + h_r) A (T_s - T_a) \tag{6}$$

Finally, heat emission from exhaust pipes can also be treated by the equations presented above by using suitable values of area, emissivity, and wall temperatures.

PARAMETERS CONTROLLING ENGINE HEAT EMISSION

Eq 3 asserts that heat emission from engine surface is a function of temperatures of air and engine surface, surface emissivity, engine surface area, and the convective heat transfer coefficient h_c. In the absence of forced air flow past the engine, h_c is a function of $(T_s - T_a)$. In the case of forced air flow, h_c is a strong function of the air velocity.

As most of the heat conducted from the burning fuel to the cylinder walls is removed by jacket water, mean engine surface temperature T_s is not much affected by surface radiation and convection. It depends essentially on the design of jacket water coolig system and water temperature. Water side heat transfer coefficients are quite high and the mean engine surface temperature is generally only a little higher than the mean jacket water temperature. Thus T_s is essentially an engine design parameter and substantially independent of the ventilation system parameters. Emissivity and surface area are also engine design features. However, emissivity depends on the surface finish and probably would not vary much

from engine to engine. But for the same power output, surface area of engine can vary considerably.

For the same bore, stroke, and speed, a two-stroke engine would be more compact than the four-stroke engine and an opposed piston engine will be more compact than either of the other two. Other things being the same, a turbocharged engine will be more compact than a naturally aspirated or mechanically supercharged engine. Hence for the same rated output, engine surface area can vary considerably.

The foregoing discussions lead to two important conclusions. Firstly, engine heat emission is a function of both engine design features and ventilation system design features. Heat emission figures cannot be accurately specified without at the same time also stating ventilating air temperature and velocity. Secondly, engine designs vary so widely that a simple relation between engine power output and heat emission which applies to all engines is unlikely.

HEAT EMISSION FROM GENERATOR

In Fig. 1, generator efficiency data from Ref 2 are shown. Many of the catalogues from engine-generator manufacturers also provided figures for generator efficiency. These values agree closely with the mean curve in Fig. 1. Thus it appears that generator efficiency is essentially a function of output alone. There are some minor effects of voltage, power factor and design features. As only the total heat emission from engine and generator is being considered, these minor effects can be ignored.

Generator heat output, Q_g, is given by

$$Q_g = \left(\frac{1-E}{E}\right)W_g \tag{7}$$

where E is the generator efficiency and W_g is the output of the generator. Q_g leaves the generator surface by both convection and radiation. Its magnitude is essentially independent of air temperature or velocity.

GUIDANCE FROM STANDARD REFERENCES

Virtually all books used by HVAC and mechanical engineers were consulted to seek their recommendations for ventilation heat load estimation. All the guidance that could be found from those sources is summarized in the following.

1. Table 5 of Ref 3 gives minimum ventilation air requirements used by one utility company(name not given). For insulated muffler and exhaust pipe and 16.7 deg C rise of ventilating air temperature from inlet to outlet, ventilation at 1.9 m³/kw is recommended. Assuming the ventilating air to be at standard conditions, this can be expressed by the following dimensionless equation:

$$Q_{et} = 0.64 \ W_e \tag{8}$$

   By calculating the generator heat emission through Fig. 1 and Eq 7, and adding it to Q_{et} from Eq 8, the total heat emission from engine and generator may be expressed as

$$Q_{egt} = 1.02 \ W_g^{0.95} \tag{9}$$

2. Eq 2 of Ref 3 also suggests another method of calculating engine losses. It amounts to a recommendation to use Eq 6 with $(h_c+h_r) = 11.4$ w/m² deg C. A value of 355 K is mentioned as usual for T_s. This suggestion is of limited value to the ventilation system designer as the engine dimensions are unknown until the final selection has been made. For this reason, no attempt to compare this method with manufacturers' data was made. Study of Table 1 in Chapter 20 of Ref 1 indicates that if there is no forced air flow over the engine surface, the recommended value of (h_c+h_r) is quite reasonable. However, if there is forced air flow over the engine, the combined heat transfer coefficient could be much higher.

3. The Equipment Volume of ASHRAE Handbook[4] gives typical heat balances for

internal combustion engines at wide-open throttle. Total heat released to room by water-cooled engines driving air-cooled electric dynamometers is given. Electric dynamometers are essentially the same as generators and hence the reported figures may be considered applicable to engine generators. The given heat emission figures may be expressed by the following dimensionless equations:

$$\text{Generator output} < 112 \text{ kw,} \qquad Q_{egt} = 0.4 W_g \qquad (10)$$

$$\text{Generator output} > 112 \text{ kw,} \qquad Q_{egt} = 0.37 W_g \qquad (11)$$

Using the curve in Fig. 1 and Eq 7, heat release from generator was calculated and subtracted from Q_{egt} given by Eq 10 and 11 to obtain the corresponding engine heat releases. The results may be expressed by the following equations:

$$W_e < 120 \text{ kw,} \qquad Q_{et} = 0.17 \, W_e^{1.1} \qquad (12)$$

$$W_e > 120 \text{ kw,} \qquad Q_{et} = 0.15 \, W_e^{1.1} \qquad (13)$$

4. An earlier edition of the DEMA Handbook[5] gives a typical heat balance for diesel engines operating at 75% to full load. The heat emission figures may be expressed as follows.

$$Q_{egt} = 0.32 W_g^{0.93} \qquad (15)$$

MEASUREMENT OF ENGINE HEAT EMISSION

The simplest method to determine heat emission from an engine would appear to be through heat balance obtained by dynamometer tests. By subtracting the work output and exhaust and jacket water heat from total heat value of fuel input, one may hope to have the remainder as the loss due to radiation and convection. However, the quantity involved is small compared to the heat value of fuel input which makes accurate estimates through this method difficult. The figures quoted by various manufacturers for surface heat emission vary from 1.5 to 9 % of the heat value of the fuel input to the engine. Even with careful measurements, errors upto ±5% in total heat balance are quite possible. Thus estimates of heat emission by this method may be in error by several hundred percent.

In one of the manufacturers' catalogues studied, it was stated that the engine heat emission had been estimated from measured engine surface temperatures. This may be considered to be a reasonable approach. None of the other catalogues clarified how the stated heat emissions had been arrived at. Verbal enquiries from some manufacturers indicate that these figures are generally arrived at by interpreting the "unaccounted" part of engine heat balance in the light of practical experience.

MANUFACTURERS' RECOMMENDATIONS

Catalogues of as many manufacturers as possible were studied for their recommendations regarding heat emissions from engines and generators. Some catalogues listed the heat emission from engines and generators separately while some gave only the total for both. In the latter case, generator losses were estimated on the basis of Fig. 1 and subtracted from the total listed to obtain the engine heat emission. Fig. 2 shows the engine heat emission as function of engine output. The name of the manufacturers have been omitted to avoid the appearance of endorsing or condemning any particular manufacturer.

Manufacturer D has stated that the engine heat emission figures listed are for ventilation air at 29 C. None of the other manufacturers has specified any particular air temperature to to which their noted heat emission figures apply. Data include both dry and wet exhaust manifolds. Some ratings are at 0.8 power factor, some at 0.9 and some at 1.0 power factor. Some ratings include heat emission from insulated exhaust pipes and mufflers while some do not. These factors cause only minor deviations and attempts for compensating for them were not made. All ratings are for 60 cycle electrical output.

All data plotted in Fig. 2 and 3 are for jacket water temperatures from 68 to 85 C. This is the range in which engines are generally operated. Higher jacket water temperature would result in   somewhat higher heat emissions.

In Fig. 2 and 3 heat emission estimates made on the basis of information in standard references, i.e. Eq 8 to 15 have also been plotted for comparison.

ANALYSIS OF FIG. 2

1. Eq 8 which is based on the recommendations of a utility company, predicts heat emissions which are far higher than those listed by any manufacturer for any engine design of any capacity. Its use will clearly result in gross oversizing of ventilation system.

2. The data for four stroke engines upto 1000 kw are correlated by the equation:

$$Q_{et} = 0.18 \, W_e \tag{16}$$

Data include both naturally aspirated and turbocharged engines with speeds ranging from 900 to 2200 rpm. This result is very useful for preliminary design purposes but rather surprising in view of Eq 3 and the earlier discussion on factors affecting engine heat emission. One would have expected that higher speed engines would have lower heat emissions than naturally aspirated ones. It must however be remembered that the data are manufacturers' recommendations and not actual measurements. The difficulties in measurement of heat emission have been pointed out earlier. Only manufacturer F has provided data for two-stroke engines. These are also correlated by Eq 16. However, a generalization on the basis of only one data set is inappropriate.

3. Eq 12 and 13 which are based on typical heat balances in ASHRAE Handbook[4] are just at the upper limit of manufacturers' data for four-stroke engines upto 1000 kw output. Hence their use in this range will always result in ventilation systems which equal or exceed manufacturers' recommendations. In some projects it is important that maximum space, cost, power consumption etc be known at an early stage. These equations are well-suited for such requirements.

4. Eq 14 which is based on a typical heat balance given by DEMA Handbook[5], is just at the lower limit of manufacturers' data for four-stroke engines upto 1000 kw output. Its use can result in considerable undersizing in some cases. Hence Eq 16 is to be preferred.

5. All data for opposed piston engines are from manufacturer B and include both naturally aspirated and turbocharged engines with speeds ranging from 514 to 1200 rpm. All these data can be correlated by a single line which gives heat emission at about 1/6 of those given by Eq 16. While opposed piston engines are more compact than four-stroke engines and hence may be expected to have a lower heat emission, an order of magnitude difference is still surprising. To the author, the difference appears to be more due to different methods of estimating than due to difference in engine design parameters.

6. Data for four stroke engines with outputs higher than 3000 kw are provided by manufacturers A, B, and C. All engines are turbocharged and are marketed as emergency power supply sources in nuclear power plants. Data of all three manufacturers are well below Eq 12, 13, 14, 16 and hence their use will result in unnnecessary oversizing of equipment. The designs and speeds of all three are comparable. Manufacturer C based estimated heat emission on engine surface temperatures while the other two have not stated how their estimates have been made.

ANALYSIS OF FIG. 3

Most of the remarks made in the analysis of Fig. 2 also apply to Fig. 3. It will further be noted that the spread of data in Fig. 3 is less than in Fig. 2. This is because the generator heat emissions are virtually independent of all other parameters except electrical output. Hence the uncertainty in predicting total

heat emission is much less than in predicting heat emission from the engine alone.

An interesting point to note is that all data can be divided into two groups. One group is clustered around the line marked as "author's recommendation for preliminary design". The other group is satisfied by the line marked as "nuclear duty" and includes four stroke turbocharged engines for emergency duty in nuclear power plants as well as opposed piston engines of manufacturer B. A similar behavior may also be noted in Fig. 2. It could be that different methods for estimation of heat emission have been used for the two groups.

DESIGN RECOMMENDATIONS

The data for many manufacturers and recommendations of standard reference hand-books have been shown graphically in Fig. 2 and 3. A simple general correlation between power output and heat emission data has not been found. Hence the ventilation system designer has to use his own judgement in using the information contained in these figures. The author recommends the curve so marked in Fig. 3 for preliminary heat load estimates. These should be superseded by manufacturer's recommendation whenever the engine-generator set to be used has finally been selected. In Fig. 3, the full load generator output should be used.

CONCLUDING REMARKS

The purpose of this paper was to provide information which may be helpful to the HVAC engineers in estimating heat loads in engine rooms at early stages of the projects. It is hoped that judicious use of material presented herein will save much time and effort and many costly design changes will be avoided.

Study of manufacturers' data in the light of theoretical considerations as well as comparison with one another has left the author in much doubt about the accuracy of those data. Reasonably good estimates should be possible by calorimetric tests in which heat removed by ventilation systems is directly measured. Availability of results of such tests would be very helpful in designing efficient and economical systems. It is hoped that this paper will stimulate some research in this rather neglected field.

NOMENCLATURE

A Surface area of engine

E Generator efficiency

h_c Convective heat transfer coefficient between engine surface and ventilating air, $kw/m^2 deg\ C$

h_r Radiation heat transfer coefficient, defined by Eq 4 and 5, $kw/m^2 deg\ C$

Q_{er} Heat emission from engine surface by radiation, kw

Q_{ec} Heat emission from engine surface by convection, kw

Q_{et} Total heat emission from engine surface by both convection and radiation, kw

Q_g Total heat emission from generator surface, kw

Q_{egt} Total heat emission from both engine and generator, kw

T_s Mean engine surface temperature, K

T_a Mean ventilating air temperature, K

W_e Engine brake output, kw

W_g Generator electrical output, kw

ϵ Emissivity of engine surface

σ Stefan-Boltzmann constant, $5.67 \times 10^{-11}\ kw/m^2 K^4$

1. ASHRAE Handbook of Fundamentals, ASHRAE, New York, 1972.
2. Baumeister, T., and Mark, L.S.,"Standard Handbook for Mechanical Engineers," p. 15-58, McGraw-Hill, New York, 1967.
3. ASHRAE Handbook and Product Directory, Equipment Volume, Chapter 32, ASHRAE, New York, 1975.
4. ASHRAE Guide and Data Book, Application Volume, p. 129, ASHRAE, New York, 1971.
5. "Standard Practices for Stationary Diesel and Gas Engines," Diesel Engine Manufacturers Association, Washington, 1958, p. 48.
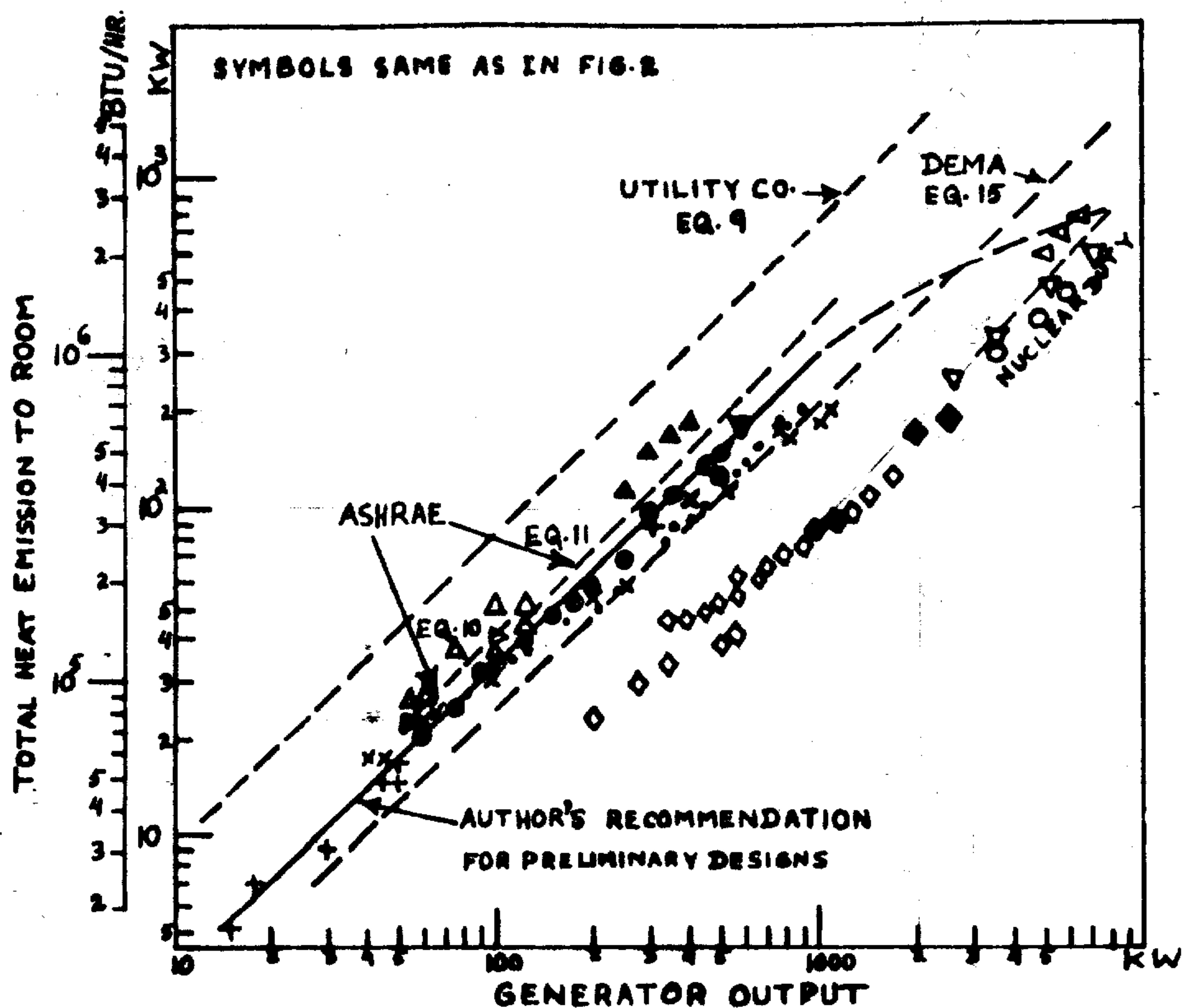
Fig. 3   Total heat emission from engine-generator sets
according to manufacturers' catalogues compared with
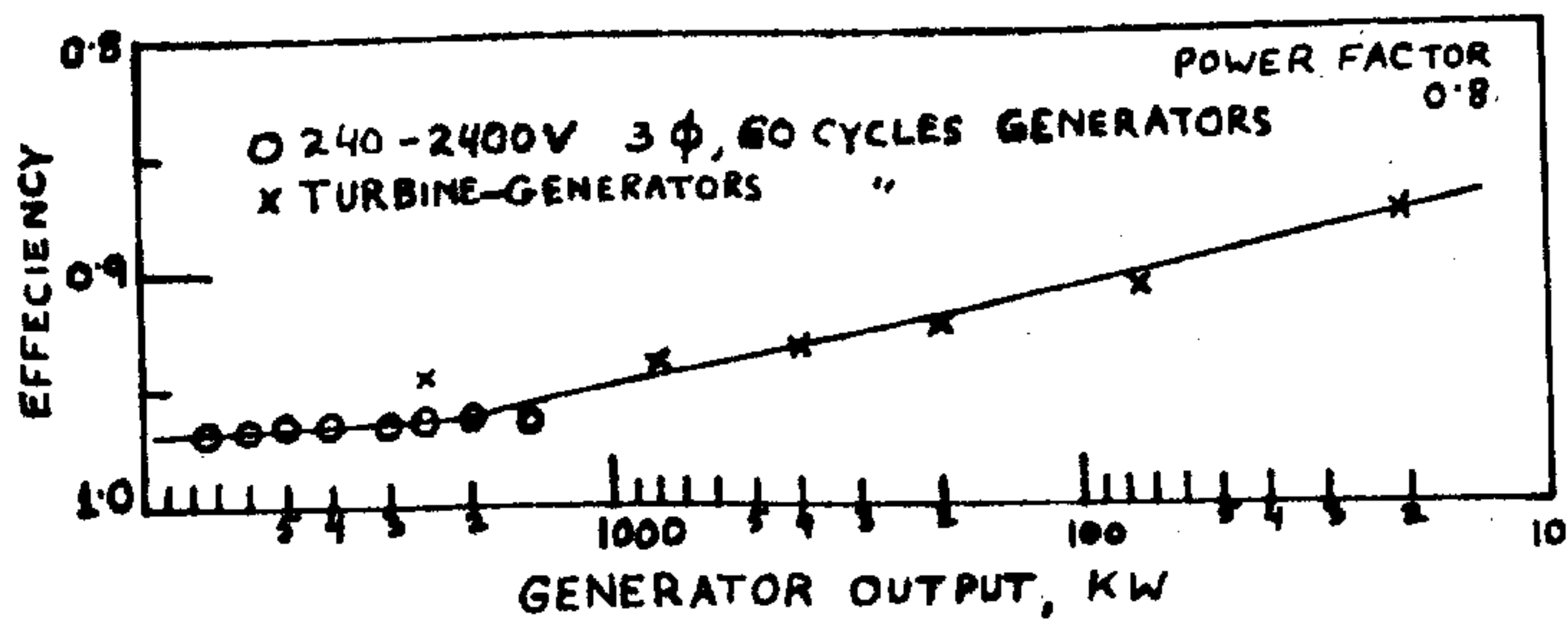various other calculation methods

163

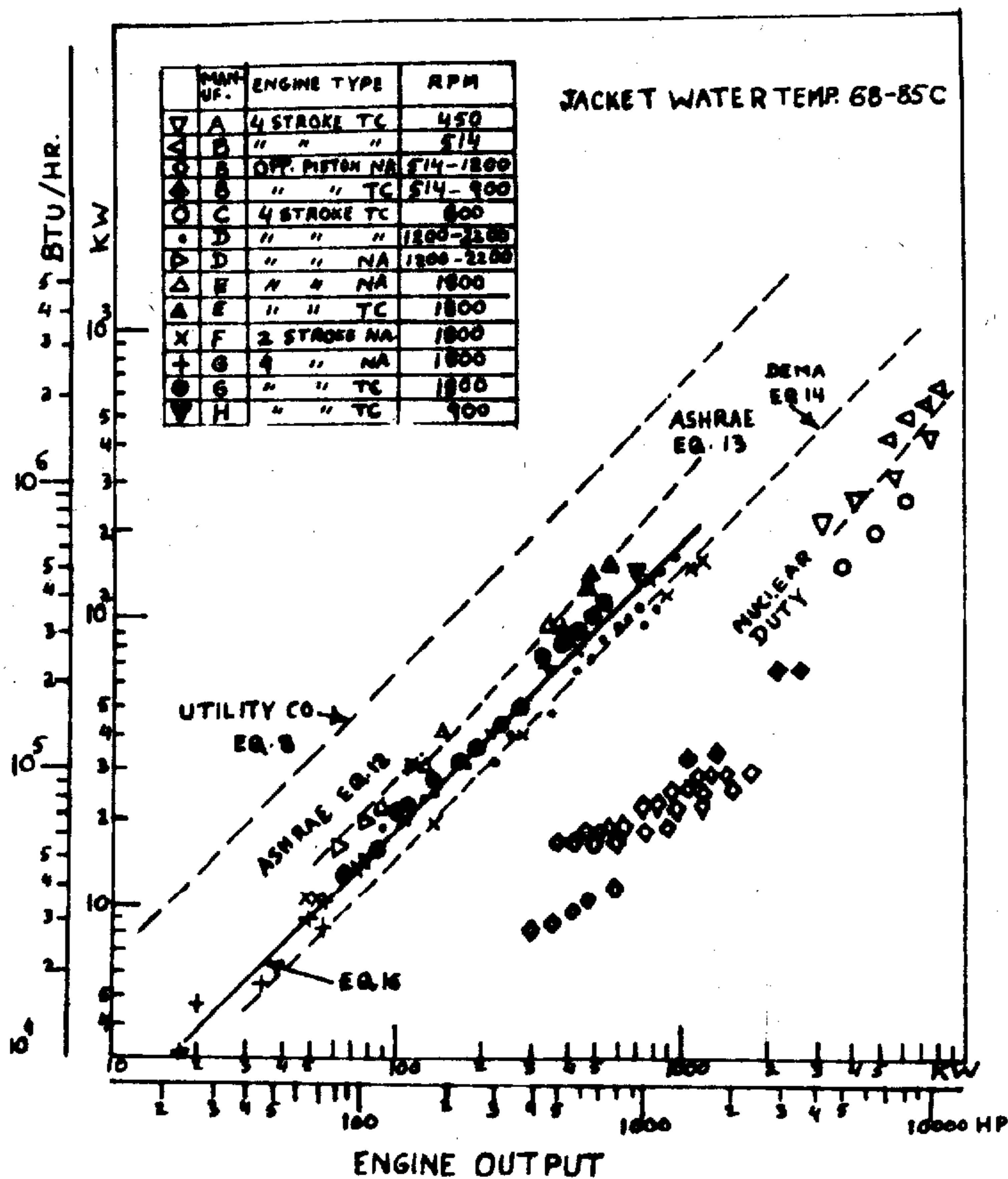Fig. 1 Efficiency of typical electrical generators from Ref 2

Fig. 2 Heat emission from engine surface
according to manufacturers' catalogues and
other estimating techniques