Weather Note

AN ESTIMATION OF THE RATIO OF ARTIFICIAL HEAT GENERATION TO NATURAL RADIATION HEAT IN SHEFFIELD

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1. INTRODUCTION

The local climate of large towns and industrial areas is influenced and modified in many ways. One major modification is brought about by artificial heat generation through combustion processes such as industrial, domestic, traffic, and human and animal metabolisms. This artificial heat generation together with absorption from natural radiation heat manifests itself in an increase of urban temperatures visible in the well-known urban heat islands. The following calculations are an attempt to assess the relationship between artificial and natural radiation heat for the Sheffield urban area. It is hoped that publication of this note will stimulate other workers in urban climatology to make similar inventories.

Early attempts to calculate the artifical heat set free by all kinds of combustion processes in a town date as far back as 1877, when Eaton [1] gave the following values for London: He argued that the 5 million tons of coal consumed in the 118 sq. mi. (188 km.^{2}) of the Metropolitan District of London would be sufficient to raise the mean temperature of a stratum of air 100 ft. (30 m.) deep resting on London, by 2.2° F. (1.2° C.). Furthermore, the vital heat of the 3,500,000 inhabitants of London would contribute an additional 0.3° F. (0.2° C.), raising the total temperature increase to 2.5° F. (1.4° C.).

In 1917 Schmidt [2] calculated that for the built-up area in Vienna the artificial heat output amounted to ⅙ to ¼ of the total solar radiation according to what was included in the built-up area. For Berlin the artificial heat amounted to even ⅓ of the solar radiation. Following in part Schmidt's methods the relationship between natural and artificial heat generation has been calculated for Sheffield as follows.

2. ARTIFICIAL HEAT GENERATION

The main sources of artificial heat generation are, first, the combustion of the different kinds of fuel and, second, heat set free by human and animal metabolisms. The most recent reasonably complete fuel consumption figures for Sheffield, divided into types of fuel and consumer groups, are available for the year 1952. Data for the consumption of solid and liquid fuel supplied by the Ministry of Fuel and Power, were used in the following calculations:

(*1*) *Heat generation from fuel consumption.*—The total fuel consumption in Sheffield in 1952 is summarized in table 1. Since, with combustion, the different kinds of fuels produce different calorie values per unit fuel, the net calorific values (cal./kg.) were calculated for the different kinds of fuels used in Sheffield from gross calorific values (B.t.u./lb.). This conversion of gross calorific into net calorific values is necessary because the combustion is incomplete, and consequently the net calorific value is smaller than the gross. (See Ministry of Power [3]). Thus for anthracite and coke it is 1 percent lower, for bituminous coal 3–4 percent, and for most fuel oils 6 percent (see Institute of Heating and Ventilation Engineers [4]). From this the estimated total heat of combustion from all fuels used in Sheffield in 1952 (obtained by multiplying the above net calorific values with the amounts of fuel converted into kg.) amounted to:

$$6.4 \times 10^{12} \text{ kg. cal.}$$

(2) *Heat generation from human and animal metabolism.*—Heat generation from human and animal metabolism is more difficult to assess. Schmidt [2] assumed that the human metabolism amounts to 2,000 kg. cal. per day

TABLE 1.—*Total fuel consumption in Sheffield—1952*

	Tons	Net calorific values
Solid fuel		
1. Industry		cal./kg.
a. Coal	1,300,075	2,595
b. Coke	187,191	3,603
2. Public institutions		
a. Coal	61,672	3,024
b. Coke	36,796	3,603
3. Domestic		
a. Coal	413,189	3,024
b. Coke	11,530	3,603
Liquid fuel		
a. Gas oil	16,100	4,636
b. Fuel oil	20,500	4,636
c. Creosote pitch mixtures	24,600	4,435

for an average person resting. However, with a body surface area of 1.7 m.^{2} and a person in motion it seems reasonable to assume the average caloric intake to be of the order of 3,200 kg. cal. per day. In 1952 the population of Sheffield was about half a million, who on this basis produced some

$$5.84\times10^{11} \text{ kg. cal yr.}^{-1}$$

If it be regarded as a fair estimation that the heat produced by the different sizes of about 30,000 animals in Sheffield is only ¼ of the heat produced by human metabolism, then for animal heat should be added

$$8.76\times10^{9} \text{ kg. cal. yr.}^{-1}$$

From the sum of these three values is obtained a total heat generation in 1952 from fuel and metabolical combustion of about

$$6.99\times10^{12} \text{ kg. cal.}$$

The urban area of Sheffield comprises some 62 sq. mi. (160 km.^{2}) out of which some 50 percent or 31 sq. mi. (80 km.^{2}) are open ground, moor and wasteland. It is self-evident that the heat in Sheffield is not uniformly distributed over the total city area, but that it is mainly produced in the built-up urban and industrial districts. It is, furthermore, clear that even these built-up areas consist not only of blocks of stone buildings, concrete, steel, and bricks, but also enclose some open spaces, e.g. roads and gardens, etc. A number of tests were carried out on large-scale maps in relation to different types of urban areas in Sheffield, to check the proportion of unit areas that were respectively built-up or open ground. From these tests it became clear that an additional 20 percent of the urban area should be subtracted as open ground within the built-up area.

Thus only 18.6 sq. mi. (48 km.^{2}), or 30 percent of the total 160 sq. mi. are left as the built-up urban and industrial areas which actually produce the artificial combustion heat, in which case 6.99×10^{12} kg. cal. per yr. were produced on an area of 48 km.^{2} or 0.48×10^{12} cm.^{2}, giving i.e., a heat production of about 14.6 kg. cal. cm.$^{-2}$ yr.$^{-1}$ in Sheffield.

3. NATURAL HEAT GENERATION

According to Landsberg [5] the annual radiation sum on a horizontal surface at latitude 54°N. is about 90,000 ly. yr.$^{-1}$ or about 90 kg. cal. cm.$^{-2}$ yr.$^{-1}$ This value, however, is given on the assumption that the sky is cloudless and unobstructed by pollution. Since this is not the case, he suggests that the actual amounts of radiation received would be from 30 percent to 90 percent lower than this.

For a more accurate assessment of the annual total solar radiation on a horizontal surface over Sheffield, Day's [6] isopleths of mean daily total of total solar radiation were used for the different months over the British Isles. From these we can calculate that the annual radiation sum on a horizontal surface over Sheffield amounts to approximately 70 kg. cal. cm.$^{-2}$ yr.$^{-1}$ (as compared with 90 kg. cal. cm.$^{-2}$ yr.$^{-1}$ which is possible at its latitude), a value very close to the values assigned to the British Isles in Landsberg's [7] generalized isolines of global radiation.

For a complete estimate of the radiation balance the outgoing or long-wave radiation must also be considered. Radiation from the earth's surface can be considered as being emitted from a black body (Monteith [8]). According to the Stefan-Boltzmann Law the total energy R emitted by a black body varies as the fourth power of the absolute temperature T:

$$R=\sigma T^4$$

where σ, a constant, has the value 1.171×10^{-7} cal. cm.$^{-2}$ day^{-1}. Thus

$$R=1.171\times10^{-7}\ T^4 \text{ cal. cm.}^{-2}\text{ day}^{-1}$$

or

$$R=4.274\times10^{-5}\ T^4 \text{ cal. cm.}^{-2}\text{ yr.}^{-1}$$

The average soil temperature (1931–60) at Sheffield (Weston Park Station) at a depth of 1 ft. is 8.8°C.; the average screen temperature (1931–60) is 9.6°C. These two values give:

270.1 kg. cal. cm.$^{-2}$ yr.$^{-1}$ (using 8.8° C., T=281.95° K.)

273.2 kg. cal. cm.$^{-2}$ yr.$^{-1}$ (using 9.6° C., T=282.75° K.)

According to Budyko [9], quoting other authorities, the radiation from most natural surfaces is 85 to 100 percent of that from a black body. If then we take radiation in Sheffield as being only 90 percent of a black body, the two values above become 243.1 and 245.9 kg. cal. cm.$^{-2}$ yr.$^{-1}$ The error from using annual values instead of the sum of daily or monthly values should be very small compared with the uncertainty regarding surface temperature and true emissivity of the ground.

A point of some importance concerns the net loss of long-wave radiation. Monteith [8] finds that throughout the British Isles

$$L=178c-200 \text{ cal. cm.}^{-2}\text{ day}^{-1}$$

where L is the net long-wave radiation, c is fractional cloudiness. This can be applied to obtain estimates of monthly or annual means of net long-wave radiation using mean values of cloudiness. Using the mean annual cloudiness figure of 5.6 oktas for Sheffield (1951–60) we obtain an average net long-wave radiation of 76 cal. cm.$^{-2}$ day^{-1}, giving 27.7 kg. cal. cm.$^{-2}$ yr.$^{-1}$ For both London and Birmingham Monteith finds an annual average of 29.6 kg. cal. cm.$^{-2}$ yr.$^{-1}$, and for Glasgow a net long-wave loss of 22.9 kg. cal. cm.$^{-2}$ yr.$^{-1}$ The estimates are, of course, negative as at these latitudes there is always a net long-wave loss.

4. CONCLUSIONS

From the foregoing estimates for the year 1952 in Sheffield, a number of points emerge assessed as follows:

1. (a) artificial radiation heat: ~14.6 kg. cal. cm.$^{-2}$ yr.$^{-1}$
   (b) short-wave radiation: ~70.0 kg. cal. cm.$^{-2}$ yr.$^{-1}$
   (c) net long-wave radiation: ~27.7 kg. cal. cm.$^{-2}$ yr.$^{-1}$
2. The net radiation balance (which is the difference between the short-wave gain and the long-wave loss) is approximately 42.3 kg. cal. cm.$^{-2}$ yr.$^{-1}$
3. The artificial radiation heat represents nearly one-third of the net radiation balance.
4. The artificial radiation heat represents approximately one-fifth of the total solar radiation receipt.
5. The artificial radiation heat counterbalances about one-half of the heat loss by net long-wave radiation.

It may be argued that these calculations can have no wider application than for the year 1952, but the difference that may exist in the proportion of natural to artificial heat generation in Sheffield in, say, 1965, is likely, in fact, to be very small. According to recent estimates fuel consumption has only slightly increased whilst population on the other hand not only has decreased slightly in numbers but also has become associated with more extended residential areas. The order of ratio as between natural and artificial radiation heat is likely therefore to show little change.

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REFERENCES

1. H. S. Eaton, "Presidential Address," *Quarterly Journal of the Royal Meteorological Society*, vol. III, No. 22, 1877, 309 ff.
2. W. Schmidt, "Zum Einfluss grosser Städte auf das Klima," *Naturwissenschaften*, vol. 30, No. 5, 1917, 494/495.
3. Ministry of Power, *The Efficient Use of Fuel*, Her Majesty's Stationery Office, London, 1958, 846 pp.
4. Institute of Heating and Ventilation Engineers, *A Guide to Current Practice*, London, 1959, 216 ff.
5. H. E. Landsberg, *Physical Climatology*, 2d ed., Gray Printing Co., Dubois, Pa., 1958, 446 pp. (p. 129).
6. G. J. Day, "Distribution of Total Solar Radiation on a Horizontal Surface over the British Isles and Adjacent Areas," *Meteorological Magazine*, vol. 90, No. 1071, Oct. 1961, pp. 269–284.
7. H. E. Landsberg, "Solar Radiation at the Earth's Surface," *Solar Energy*, vol. V, No. 3, July–Sept. 1961, pp. 95–98.
8. J. L. Monteith, "An Empirical Method for Estimating Long-Wave Radiation Exchanges in the British Isles," *Quarterly Journal of the Royal Meteorological Society*, vol. 87, No. 372, Apr. 1961, pp. 171–179.
9. M. I. Budyko, *Teplovoĭ Balans Zemnoĭ Poverkhnosti* [Heat Balance of the Earth's Surface], Leningrad, 1956 (English translation by N. A. Stepanova, U.S. Weather Bureau, 1958).

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