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Conversion of Exhaust Heat to Latent Heat for the Management of the Thermal Environment in Urban Areas

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ABSTRACT

In this paper, the conversion of exhaust heat to latent heat is studied as one of the methods for the preservation of the thermal environment in urban areas. A simulation model of exhaust heat management is composed and applied to the soot-and-smoke emitting facilities in the Tokyo Metropolitan Area. The effectiveness is estimated by indices of "coefficient of exhaust heat management" and "conversion ratio of exhaust heat to latent heat".

1. INTRODUCTION

In urban areas, a large amount of energy is needed to maintain complex activities. This leads to environmental problems, where atmospheric temperature rises, relative humidity drops, wind conditions change, etc. It is considered that the major changes in a thermal environment have the following causes:

(1) generation of exhaust heat by energy consumption;

(2) alterations in land-use.

The mean value of energy consumption in the Tokyo Metropolitan Area is approximately 740 kcal/m^2 per day, which corresponds to 25% of the insolation from the whole sky.

Furthermore, regarding urbanized land use, such as commercial, industrial and residential, the percentage was 50% in 1955, and thereafter increased to 66% by 1980. Migration to the cities is expected to become more intense, which will bring about various problems related to thermal environment.

However, it is very difficult to respond technically to problems of thermal environment in urban areas, because energy consumption is ultimately tied to heat exhaust.

In this paper, the relationship between thermal environment and energy consumption in urban areas is observed, and methods for the preservation of the thermal environment are studied.

The authors simulate the conversion of exhaust heat to latent heat with water evaporation and estimate its efficiency.

2. METHODS FOR THE PRESERVATION OF THE THERMAL ENVIRONMENT IN URBAN AREAS

Methods for the preservation of the thermal environment are classified into the following items [1, 2].

(1) Reduction of exhaust heat in urban areas:
— technical answers;
— changes in the structural organization of the cities;
— changes of life-style.

(2) Neutralization of exhaust heat:
— conversion of exhaust heat to latent heat;
— conversion of exhaust heat to radiant heat.

(3) Control of solar radiation:
— rise in albedo;
— direct use of solar energy (e.g., for heating, etc.).

Among these items, it seems that reduction of exhaust heat is the most adequate one. However, when energy demands increase in urban areas, the adoption of this method is very difficult. The neutralization of exhaust

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heat will be discussed as follows: although latent heat has an indirect influence upon the thermal environment, and it brings about an increase in the thermal capacity of the air, it is not directly connected to a rise in atmospheric temperature. This method, which converts exhaust heat to latent heat, can be easily put into practice through the replacement of dry-cooling by wet-cooling systems [3–5].

In this paper, the conversion of exhaust heat to latent heat is studied as a method of thermal environment management.

3. SIMULATION MODEL OF EXHAUST HEAT MANAGEMENT

3.1. Composition of the model

This model is composed of the following three processes:

(1) heat exchange from sensible heat in exhaust heat to cooling water;

(2) cooling-water circulation;

(3) wet-cooling towers emitting latent heat to the atmosphere.

For controlling the exhaust heat management processes, excess energy is required. Therefore, in order to compose the simulation model, the methodology for obtaining excess energy as well as the heat balance must be considered.

The simulation model shown in Fig. 1 involves generation systems utilizing energy of exhaust heat as well as water purification and power plants supplying water and electric power required for exhaust heat management. By this model, it is possible to estimate the efficiency and influence in exhaust management.

3.2. Equations and calculation method of the model

(1) Objective function

The aim of exhaust heat management is to estimate the amount of resultant latent heat. Therefore, it is appropriate as an objective function to take the ratio of the resultant latent heat to the original amount of exhaust heat in the conversion:

$$P = L_H/H$$

where

P = portion of the exhaust heat converted into latent heat

H = exhaust heat used in the conversion (kcal)

L_H = resultant latent heat (kcal).

Optimization of the objective function is given by $P \rightarrow \max$.

(2) Restrictive conditions

As the system of exhaust heat management consumes energy in its operation, exhaust heat is generated from the system itself. Therefore, a restrictive condition of the model is that the heat value, which is generated in the process, is smaller than that of the resultant latent heat:

$$R = [G_H + h_2(E_2 + E_3)]/L_H$$

where

R = coefficient of exhaust heat management

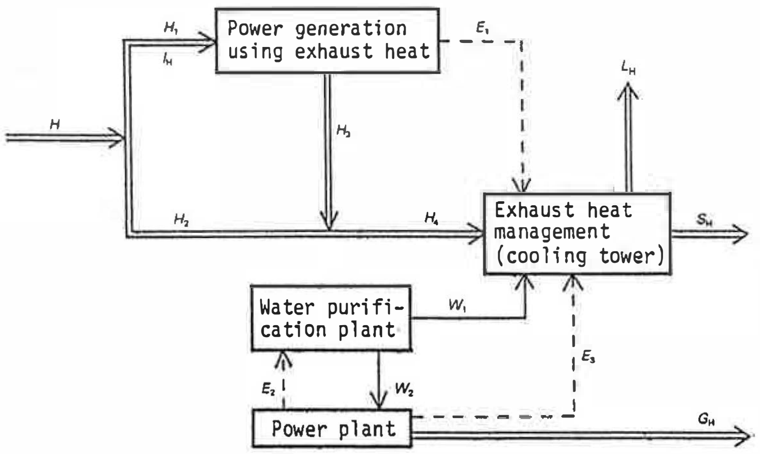

Fig. 1. System composition of exhaust heat management.

G_H = exhaust heat value at power plant (kcal)
h_2 = calorific value of electric power (kcal/kWh)
E_2 = electric power for water supply at water purification plant (kWh)
E_3 = electric power purchased for exhaust heat management (kWh).
By the restrictive conditions,

$$R < 1 \quad \text{and} \quad R \to \text{min}.$$

Furthermore,

$$W_1 + W_2 < W_{max}$$

where
W_1 = water used for exhaust heat management
W_2 = water used for power generation
W_{max} = maximum water supply value attained for exhaust heat management.

(3) Calculation method

Figure 2 shows the flowchart of the model for exhaust heat management. Input data are exhaust heat values grouped by month and temperature level. Each formula is calculated monthly. Table 1 shows parameters and Table 2 shows set-up values.

3.3. Sensitivity analysis

(1) Influences of exhaust heat temperature

A sensitivity analysis is done by setting a constant exhaust heat value to each month.

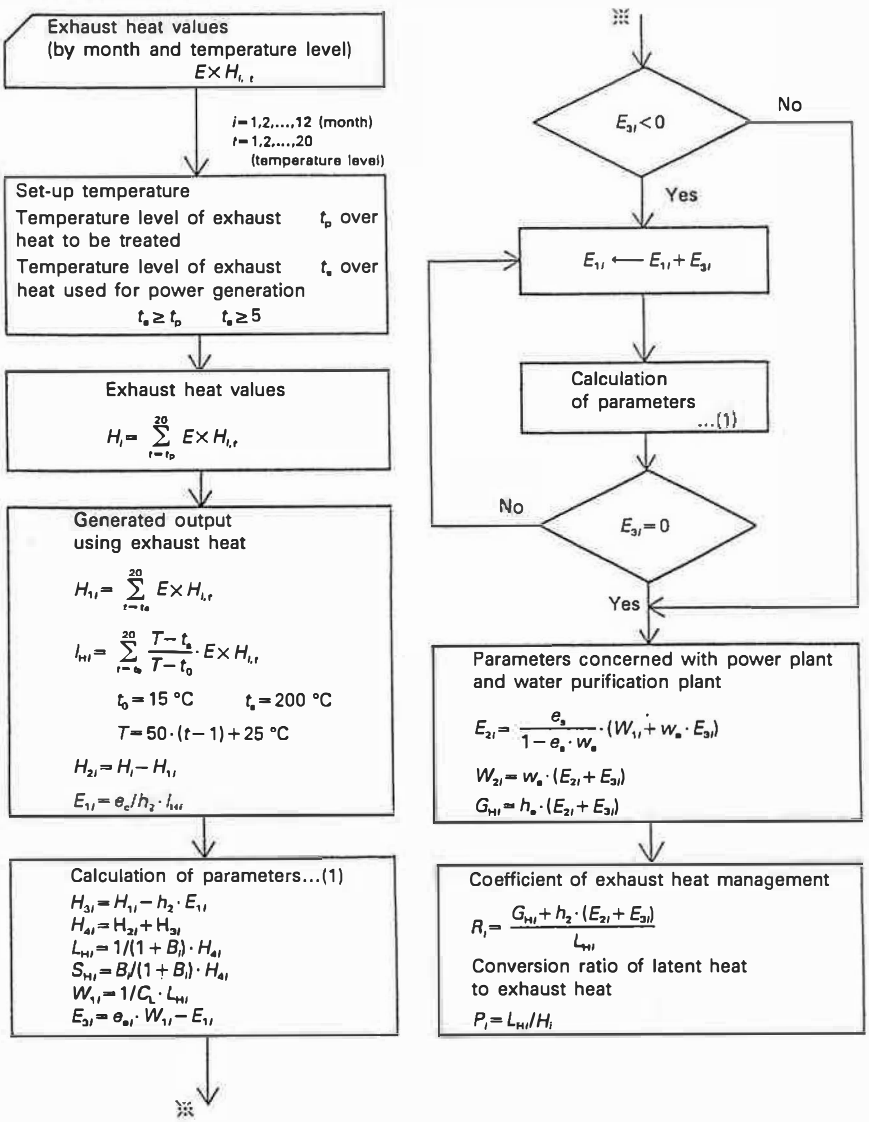

Fig. 2. Flowchart of exhaust heat management model.

TABLE 1

Parameters

H	exhaust heat used in the conversion
H_1	exhaust heat used for power generation
I_H	enthalpy of H_1
H_2	$(=H-H_1)$
H_3	exhaust heat after power generation
H_4	$(=H_2+H_3)$
E_1+E_3	electric power used for exhaust heat management
E_1	generated power
E_3	purchased power
E_2	electric power for water supply at water purification plant
W_1	water used for exhaust heat management
W_2	water used for power generation
L_H	resultant latent heat
S_H	sensible heat
G_H	exhaust heat at power plant
B	Bohen ratio
C_L	latent heat of vaporization
W_e	water consumption at power plant
e_c	thermal efficiency of power generation by exhaust heat
e_e	electric power consumption per evaporated water
e_s	electric power consumption at water purification plant
h_2	calorific value of electricity
h_e	exhaust heat at power plant
i	month $(i=1, 2, \ldots, 12)$
t	temperature level rank of the exhaust heat $(t=1, 2, \ldots, 20)$
R	coefficient of exhaust heat management
P	conversion ratio of exhaust heat to latent heat

TABLE 2

Set-up values

$C_L = 0.58$ Gcal/m^3
$e_c = 0.15$
$h_e = 1.59$ Mcal/kWh
$h_2 = 0.86$ Mcal/kWh
$e_s = 0.39$ kWh/m^3
$W_e = 0.21$ m^3/kWh

Figure 3 shows annual mean coefficients of exhaust heat management. When exhaust heat is not utilized for electric generation, heat equivalent to 19% of that which is converted from exhaust heat to latent heat is generated. When the ratio of exhaust heat used for power generation is constant, rises in temperature levels of the exhaust heat are accompanied by reductions in the values of exhaust heat management coefficients.

However, the coefficient never reaches 0 due to electric power demands at the water purification plant. Figure 4 shows the annual mean conversion ratio of exhaust heat to latent heat, which indicates minimum values of approximately 74%.

(2) Influence of the generating efficiency

Figure 5 shows the relationship between generating efficiency and coefficients of ex-

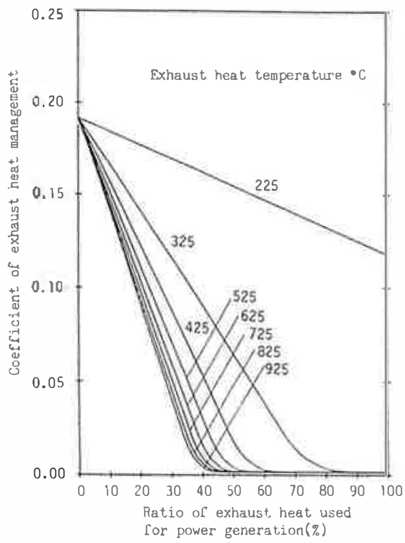

Fig. 3. Coefficients of exhaust heat management.

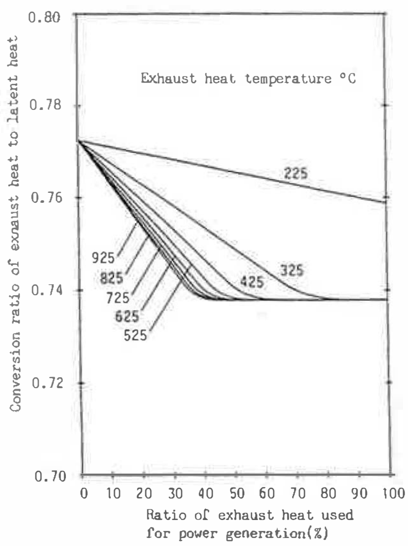

Fig. 4. Conversion ratio of exhaust heat to latent heat.

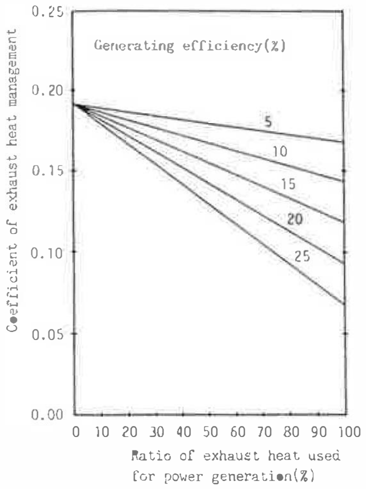

Fig. 5. Relationship between generating efficiency and coefficients of exhaust heat management (in case of exhaust heat temperature 225 °C).

haust heat management. The exhaust heat temperature is set at 225 °C. As the generating efficiency increases, the coefficient of exhaust heat management decreases.

In Fig. 6, the temperature level of the exhaust heat is 325 °C. The coefficient of exhaust heat management may be lowered to 0.025 by using 100% of the exhaust heat for generation, even at an efficiency of 10%. It is considered that the coefficient of exhaust heat management is influenced by the efficiency of electric power generation and by the temperature level of the exhaust heat.

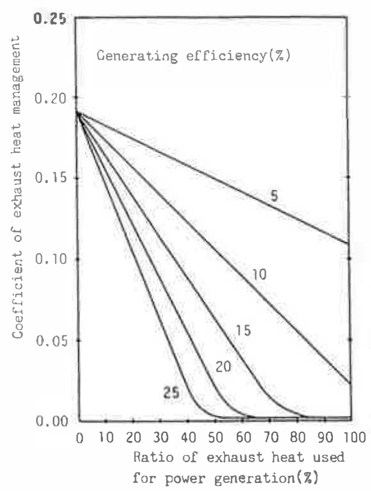

Fig. 6. Relationship between generating efficiency and coefficients of exhaust heat management (in case of exhaust heat temperature 325 °C).

4. APPLICATION OF THE MODEL TO SOOT-AND-SMOKE EMITTING FACILITIES IN THE TOKYO METROPOLITAN AREA

The model of exhaust heat management is applied to the exhaust heat of 5220 soot-and-smoke emitting (SSE) facilities (see Appendix) in the Tokyo Metropolitan Area. The effects and limitations of the conversion to latent heat are analyzed.

4.1. Heat exhaust by soot-and-smoke emitting facilities

Table 3 shows energy consumption and exhaust heat values for the various types of SSE facilities. The sensible heat contained in exhaust heat is calculated as the holding heat value of dry exhaust gas:

$$S_{Hi} = G_i \cdot C_p(T_i - T_0) \cdot L_i$$

where
S_{Hi} = sensible heat value at facility i (kcal/month)
G_i = quantity of exhaust gas at facility i (Nm^3/h)
C_p = specific heat of exhaust gas (kcal/Nm^3 °C)
T_i = temperature of exhaust gas at facility i (°C)
T_0 = temperature of atmospheric air (°C)
L_i = the number of monthly operation hours at facility i (h/month).

G_i, T_i and L_i are given by the data of SSE facilities. C_p and T_0 are set up as 0.33 and 15. The latent heat in exhaust heat is also calculated, based on vapor generation at perfect combustion. It can be written as follows:

$$L_{Hi} = (F_{ij} \cdot W_j \cdot C_L) \qquad (j = 1, m)$$

where
L_{Hi} = latent heat value at facility i (kcal/month)
F_{ij} = quantity of fuel j consumption at facility i (l/month, Nm^3/month, kg/month)
W_j = quantity of water vapor generated by combustion of fuel j (kg/l, kg/Nm^3, kg/kg)
C_L = latent heat value of water evaporation (kcal/kg)
m = number of fuel type.

Table 4 shows sensible and latent heat values of exhaust heat at 50 °C intervals. The major portion of the exhaust heat accounts for temperatures lower than 300 °C. From Fig. 7, which shows monthly values of exhaust heat,

TABLE 3

Energy consumption and exhaust heat value at soot-and-smoke emitting facilities in the Tokyo Metropolitan Area, 1980

Classification	Energy consumption	Quantity of exhaust heat (Tcal/year)	
		S_H	L_H
A — industrial			
1 Electricity	18270.0	810.2	1081.8
2 Gas	762.7	55.4	56.7
3 Mining	0.0	0.0	0.0
4 Food, tobacco	1588.2	167.2	102.7
5 Textile industry	234.0	30.8	13.6
6 Wood, wooden products	508.6	92.2	36.2
7 Pulp, paper	1438.5	103.1	81.9
8 Publication, printing	283.1	39.4	18.7
9 Chemical industry	1548.8	194.2	93.4
10 Petroleum, coal products	26.9	5.0	1.6
11 Rubber products	106.9	11.1	6.3
12 Leather, leather products	40.2	4.0	2.4
13 Ceramic	523.5	141.4	30.7
14 Iron and steel industry	2260.5	412.4	103.5
15 Nonferrous metals	1016.9	15.4	5.6
16 Precision machinery	55.4	8.2	3.2
17 Electric machinery	42.7	10.0	2.8
18 Transport	75.9	10.8	5.0
19 Metal products	111.2	11.1	7.0
20 Manufacturing (except 4 - 19)	148.3	19.8	8.9
21 Insurance, waste treatment	3039.2	731.5	764.0
22 Others	143.5	16.3	9.4
A Total (1 - 22)	31299.0	2889.4	2435.4
B — commercial and residential			
23 Hotel	557.7	143.6	37.1
24 Medical facilities	649.7	154.8	41.9
25 Multiple-dwelling house	169.7	69.5	10.3
26 Dormitory	66.3	19.3	4.0
27 Heat supply	352.1	46.0	33.1
28 Office, school, etc.	2422.8	525.8	171.6
29 Others	1051.2	288.4	104.3
30 Public bath	1423.3	1.0	100.9
B Total (23 - 30)	6690.7	1248.5	503.1
Sum total (A + B)	37958.0	4137.8	2938.4

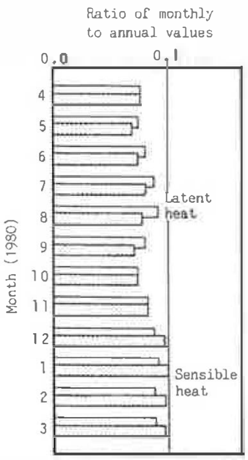

Fig. 7. Monthly values of exhaust heat at soot-and-smoke emitting facilities.

it can be seen that sensible heat values become higher in winter.

4.2. *Application and results*

For the application of the model to the SSE facilities in the Tokyo Metropolitan Area, Fig. 8 shows changes in the coefficients of exhaust heat management, which depend on the temperature levels of exhaust heat: that used for electric power generation as well as that taken up for processing. The coefficient of exhaust heat management decreases as the temperature limit of the exhaust heat used for power generation decreases, and also as the temperature level of the exhaust heat taken up for processing increases.

TABLE 4

Annual exhaust heat values at soot-and-smoke emitting facilities

Temperature level (C)	Sensible heat (S_H) (10^3 Gcal)	Latent heat (L_H) (10^3 Gcal)	S_H/L_H
15 - 50	23.40	238.69	0.0981
50 - 100	229.35	141.99	1.6153
100 - 150	1088.70	1158.30	0.9399
150 - 200	621.41	283.05	2.1954
200 - 250	847.59	527.31	1.6074
250 - 300	739.70	465.26	1.5899
300 - 350	212.39	49.11	4.3247
350 - 400	71.71	12.78	5.6115
400 - 450	109.37	11.82	9.2553
450 - 500	93.57	28.59	3.2728
500 - 550	28.69	3.71	7.7343
550 - 600	44.39	13.36	3.3215
600 - 650	7.94	0.76	10.3940
650 - 700	4.00	1.24	3.2332
700 - 750	9.59	1.84	5.2208
750 - 800	2.04	0.13	15.2726
800 - 850	1.11	0.21	5.1993
850 - 900	0.00	0.00	—
900 - 950	0.02	0.10	0.1627
950 -	2.89	0.14	20.3268
Total	4137.84	2938.40	1.4082

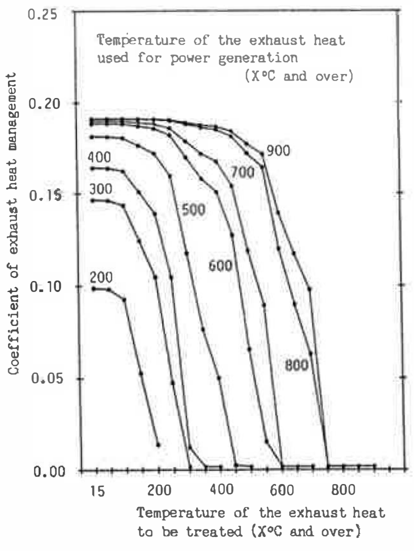

Fig. 8. Coefficients of exhaust heat management applied for soot-and-smoke emitting facilities in the Tokyo Metropolitan Area.

When the temperature levels of exhaust heat used for processing and for power generation are equalized, the coefficient of exhaust heat management reaches its minimum value of approximately zero. Therefore, it is clear that maximizing the use of exhaust heat for power generation is effective in terms of conversion from exhaust heat to latent heat.

Figure 9 shows changes in the conversion ratio of exhaust heat to latent heat that depend on the temperature levels of the exhaust heat which is used for power generation and which is taken up for processing. It can be seen that around 72% of exhaust heat is converted to latent heat even at the minimum.

In Figure 10 the ratio of sensible heat to latent heat is compared between present exhaust values and estimated values. The ratio

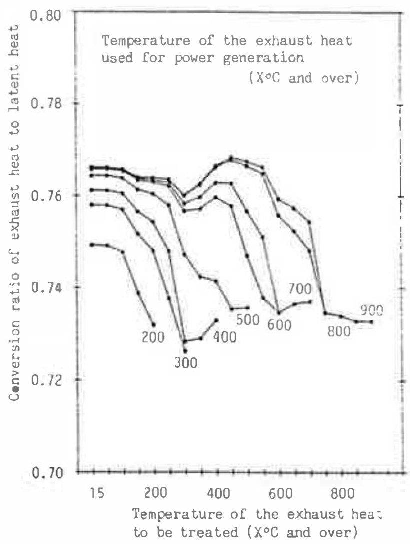

Fig. 9. Conversion ratio of exhaust heat to latent heat.

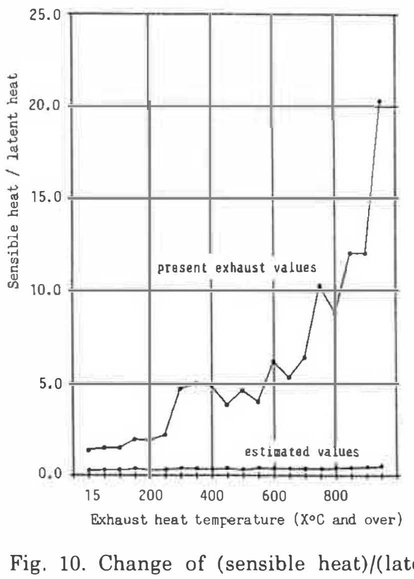

Fig. 10. Change of (sensible heat)/(latent heat) by exhaust heat management.

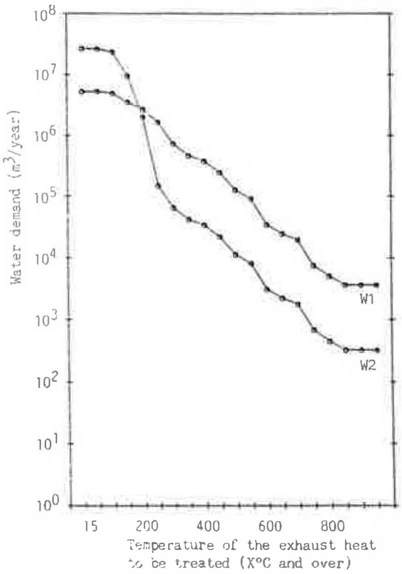

Fig. 11. Water demand for exhaust heat management.

decreases substantially at all temperature levels, which is evidence of the effect of exhaust heat management.

Figure 11 shows water demand for exhaust heat management. The maximum value of annual water demand, which includes water for exhaust heat management (W_1) and for electric power generation (W_2) reaches 32 million m^3 per year. This value approximately accounts for 2.5% of the quantity of water supplied in the Tokyo Metropolitan Area. So, it is considered that the limitation of exhaust heat management by water supply is comparatively low.

5. CONCLUSIONS

In this paper, a simulation model of exhaust heat management is proposed and its efficiency for the SSE facilities is studied. The results are summarized as follows:

(1) It is mentioned that the conversion of exhaust heat to latent heat is one of the likeliest methods for thermal environment management in an urban area.

(2) The simulation model, which includes the conversion process of exhaust heat to latent heat, is set up to estimate the effectiveness and influence in exhaust heat management.

(3) The effectiveness is estimated by the indices of "coefficient of exhaust heat management" and "conversion ratio of exhaust heat to latent heat".

(4) As a result of applying the model to the SSE facilities in the Tokyo Metropolitan Area, it is clear that maximizing the use of exhaust heat for power generation is effective in terms of exhaust heat to latent heat.

(5) As one of the restriction conditions, water demand for exhaust heat management is calculated.

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APPENDIX

In accordance with the "Air Pollution Control Law" of Japan and the enforcement ordinances related to it, a facility which is installed in an industrial plant or business establishment and which generates and emits soot and smoke is defined as a "soot-and-smoke emitting (SSE) facility". The proprietors and operators who manage the SSE facilities are obliged to report the following items to the authorities: the kind and type of facility, the quantity of air pollutants, the energy consumption by month, the quantity of exhaust gas per hour, the temperature of exhaust gas, the numbers of hours the facility is in operation, the classification of the plant, and the plant's location by mesh longitude and latitude. The energy consumption by the SSE facilities is nearly a half of the whole amount of that used by industry in the Tokyo Metropolitan Area.