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ENERGY AND MATERIAL USE IN THE PRODUCTION OF INSULATING GLASS WINDOWS

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(Communicated by Andreas Athienitis)

Abstract—Waste heat, waste material, and waste water are estimated for the production of glass sheets and aluminum frames for architectural window systems. The purpose is to compare the wasted energy and matter in the production process and the heat loss through the window systems. Raw materials, fossil fuels, and fresh water are inputs, while waste heat, waste material, and waste water in addition to the products are outputs. Waste heat of 16.9 MJ versus 502.5 MJ, waste materials of 0.7 kg versus 5.4 kg, and waste water of 0.05 m^3 versus 0.37 m^3 are given off in the production of a glass sheet of 1 kg versus an aluminum frame of 1 kg. A comparison of a single glazed window and a double glazed window was made in terms of the waste heat at the production stage and the heat loss through the windows. It was found that the sum of the waste heat and the heat loss in the case of a double glazed window becomes smaller than in the case of a single glazed window within the first winter season in Tokyo. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

The luminous and thermal performance of architectural windows affects electric power consumption for lighting, heating, and cooling systems in buildings. Therefore, new window glazing materials have been developed extensively over the last 10 yr. Computer simulation with regard to room air temperature and space heating load has confirmed that these newly developed materials are promising (Wilke and Schmid, 1991; Wakabayashi *et al.*, 1993).

Nevertheless, the use of thermally well-insulated glazing materials in newly built homes in Japan is not matured yet except in Hokkaido, the northernmost island (FGMAJ, 1994). One reason for this is that double-glazed windows, whether with low-emissivity coating or not, are still very expensive in Japan and some consider that the pay-back period is too long. From the viewpoint of energy and environmental issues, however, it is necessary to consider the pay-back period in terms of the total use of energy and matter during the whole period of production and use, possibly even including disposal. Such considerations should reflect the cost of insulated windows.

The purpose of this article is to outline how the production systems of window glazing materials such as glass sheets and aluminum frames work. Finally, we make a comparison of the total waste heat of a single glazed window with that of a double glazed window.

2. PRODUCTION SYSTEM

In a production system, as illustrated in Fig. 1, not only raw materials are supplied, but also fossil fuels and fresh water are supplied to treat the raw materials for the purpose of producing a product. A certain amount of raw materials become a part of the product, such as a glass sheet or an aluminium frame, while at the same time the rest is dumped as waste materials into the environment. There may be a case in which energy as input fossil fuels is fixed as a part of the product, but in most cases it is dumped into the environment as waste heat. Fresh water is usually required for dumping waste heat and waste materials efficiently, because water is a substance which can deliver a large amount of heat when evaporating and can solve various substances when mixed.

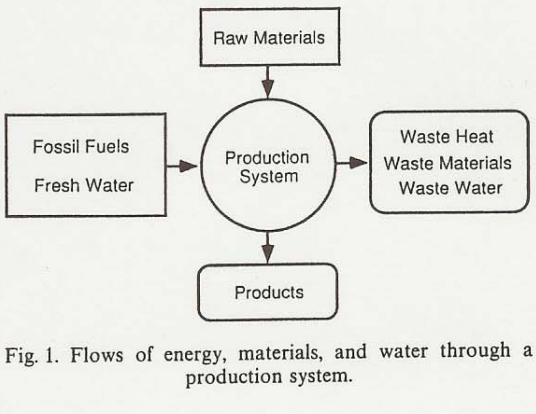

Fig. 1. Flows of energy, materials, and water through a production system.

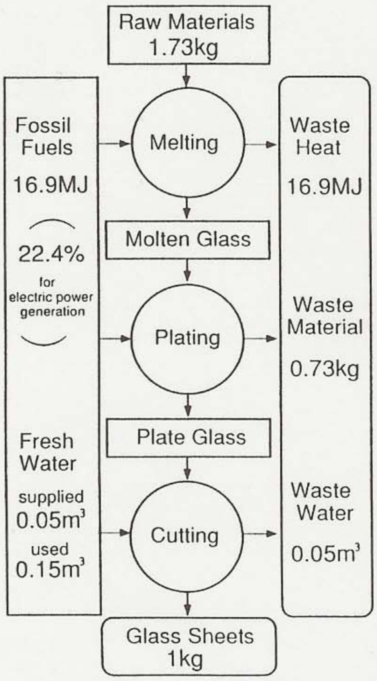

Fig. 2. Production of 1 kg of glass sheets.

environment. Most of the waste glass among the waste materials is used again as a recycled raw material.

3.2. Production system of aluminum frames

Figure 3 shows the flow of the estimated energy, materials, and water through the production system for 1 kg of aluminum frames. Alumina of 2.9 kg requires bauxite of 6.4 kg; an ingot of 1.5 kg requires alumina of 2.9 kg; and an aluminum frame of 1 kg requires an ingot of 1.5 kg. The differences, 3.5 kg from bauxite to alumina, 1.4 kg from alumina to ingot, and 0.5 kg from ingot to the frame, are dumped as waste materials. The total of the waste materials is 5.4 kg.

Among the nine processes electric power is consumed most in the process of producing an ingot from alumina, namely electrolysis. In Japan, there is only one factory that refines aluminum; it uses the hydro-electric power generated within its own site (JAF, 1992). The reason for this is the electric power from the grid is expensive. A total waste heat of 503 MJ is given off during the production process of aluminum frames of 1 kg; this is 30 times the total waste heat in the production process of glass sheets of 1 kg.

There are usually two casting processes in the production system of aluminum frames: the first is for aluminum ingots and the second for frames. This is because the casting factories usually exist separately.

3.3. Estimation for the waste heat, waste material, and waste water of window systems

We assumed a window system of 1.2 m^2 including both glass and frame. The glass part is 1.02 m^2 and the frame part is 0.18 m^2. A comparison was made for three types of window. The first type is single glazed with an aluminum frame; the second is double glazed with an aluminum frame; and the third is double glazed with a wooden frame. A glass sheet was assumed to be 3 mm thick. A single pane weighs 7.6 kg and double panes 15.2 kg. The mass of an aluminum frame was determined to be 4.1 kg, assuming the sectional shape of a typical aluminum frame available commercially.

Figure 4 shows the estimated amounts of the waste heat, waste material, and waste water when the three types of window system are produced. We assumed that the waste heat in the case of the wooden frame is one tenth of that of the aluminum frame, although there is a study claiming that the manufacturing process of a wooden frame from a fully-grown tree requires only 0.3%–0.8% of the fossil fuels for producing the aluminum frame (Arima, 1994). We assumed that negligible amounts of waste material and waste water are dumped when the wooden frame is produced.

The amounts of waste heat, waste material, and waste water in the case of Type 2 are larger than those of Type 1 because Type 2 is a double glazed window. The waste heat in the case of Type 2 is larger than Type 1 by 6%. The waste material and waste water in the case of Type 2 is larger than Type 1 by 20%. A smaller increase in waste heat than in waste material and waste water is because the waste heat caused by the production of an aluminum frame is much greater than that for a glass sheet. The mass of two glass sheets, 15.2 kg, which weigh more than three times that of the aluminum frame, causes a larger increase in waste material and waste water than in waste heat. The difference in waste heat between Type 2 and 3 is very large, as we assumed a small amount of waste heat in producing the wooden frame.

3.4. Heat loss through the window systems

We investigated how much heat is lost through the windows from each of the above three types of window systems under the

We tend to take a look only at the relation of input fossil fuels to the final product, but it is also very important for us to take a look at the relation of input fresh water and raw materials to the waste heat, the waste materials, and waste water.

Here we presume that the production system of glass sheets consist of three processes: melting, plating and cutting. Raw materials such as silicate materials are first mixed and melted in a fireplace. Glass sheets are made by pouring liquid glass onto a flat table made of metal such as tin and by rolling it onto the sheets. The sheets are ground flat and polished on both sides (Pauling, 1970). The final process is cutting the glass sheets. The production system of aluminum frames is presumed to consist of processes such as crushing, ignition, electrolysis, casting and treatment from bauxite to the final product.

The raw materials are usually obtained after being mined, transported, and refined. The same is true of fossil fuels. In contrast, the final products are transported to a building site and may be assembled with other building elements. Such activities necessarily require the use of energy. It is a question whether or not such energy use should be included in the analysis. Another question emerges instantaneously: whether or not the energy use for manufacturing the machines for mining and that for manufacturing the trucks and ships for transportation should be included in the analysis. One can raise similar questions to the above again and again and it could be limitless. It is therefore very important to confine a production system to a certain limited system on which we can focus. We excluded the energy for mining and transporting the raw materials to be supplied to the production systems defined above and also excluded the energy for transporting the middle products from one factory to another and the final products to a building site.

We collected the data of the total amounts of silica, dolomite and waste glass as raw materials in mass to be supplied on an annual basis to the production system of glass sheets in Japan from one of the yearbooks published by MITI (1992a). The number of glass sheets produced in Japan was also obtained from this yearbook. We also collected the data of the total amounts of light oil, heavy oils of class A, B, and C, coal, liquified natural gas (LNG), liquified propane gas (LPG), steam, and electricity used during the production of glass sheets in Japan from another yearbook also published by MITI (1992b). We converted the steam and the electricity from secondary energy sources into primary energy sources, assuming that the steam is produced by boilers having the thermal efficiency of 80% and the electricity by oil-fired power plants having the thermal efficiency of 35% including transmission loss. The data of the total amounts of the used and the supplied water were also obtained from the MITI's yearbook (1992b).

In a similar manner, we collected the data regarding aluminum frames as a final product from the yearbook published by JAF (1992). The data of fossil fuel use and fresh water use associated with the production of aluminum frames was obtained from the MITI's yearbook (1992b).

All of the statistics available from the yearbooks published by MITI are included in the total mass used for manufacturing throughout Japan. Some manufacturing plants could be more efficient than others, but such statistics were not available. Therefore we calculated the average masses of raw materials, fossil fuels, and fresh water which were used in the production of glass sheets and aluminum frames of 1 kg at a plant with an average efficiency. The amount of waste materials was assumed to be the difference in mass between the raw materials and the products. The amounts of waste heat and waste water were assumed to be exactly the same as those of fossil fuels and fresh water supplied to the production system.

3. RESULTS AND DISCUSSION

3.1. Production system of glass sheets

Figure 2 shows the flows of estimated energy, materials, and water through a production system for 1 kg of glass sheets.

Fossil fuel of 16.9 MJ is required for producing 1 kg of glass sheets. The waste heat, the amount of which is equal to fossil fuel of 16.9 MJ, is dumped into the environment. A portion, 22% of the fossil fuel supplied, is used to generate electric power to be used by the production system. The amount of supplied water, 0.05 m^3 for the product of 1 kg, is equal to that of waste water. The total of the used water is 0.15 m^3 so that 0.1 m^3 of water is recycled within the production system. The difference between the raw materials of 1.73 kg and the glass sheets of 1 kg as a final product is dumped as waste materials of 0.73 kg into the

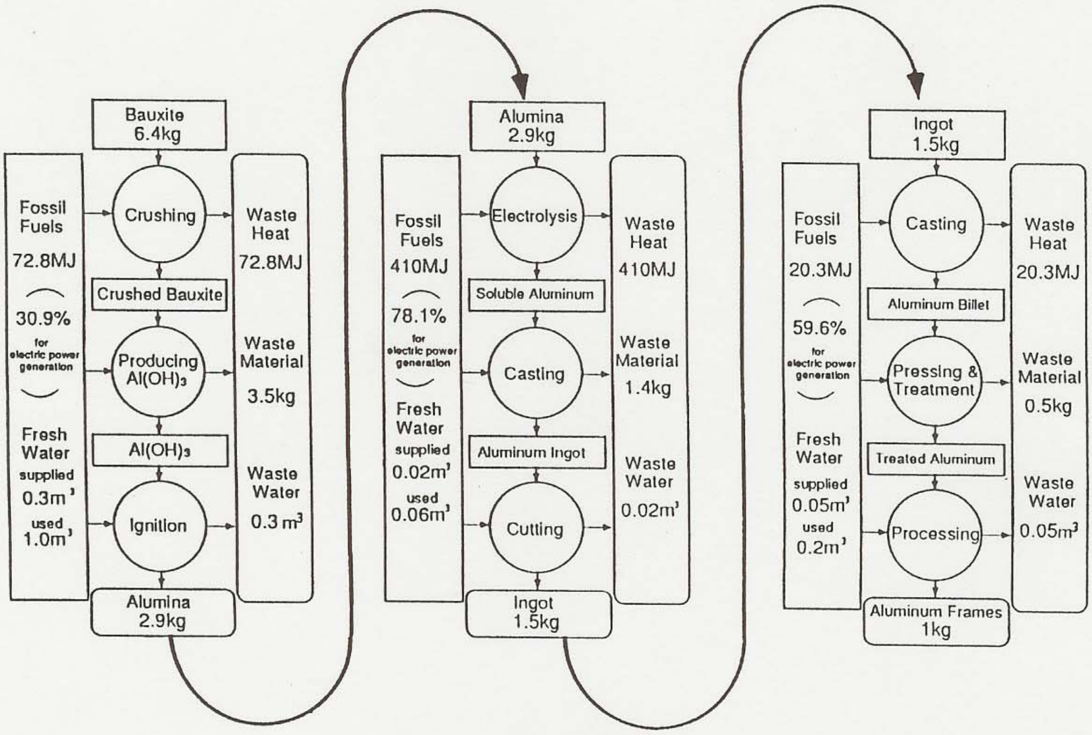

Fig. 3. Production of 1 kg of aluminum frames.

weather conditions during the winter in Tokyo. In most of the residential buildings in the Tokyo area in Japan, the energy use for space heating is dominated. The amount of energy used for space cooling is very small even if the summer in the Tokyo area is very hot and humid. This is because most Japanese people living in this area use air conditioners for a rather short period, especially during the evening hours. As far as the residential buildings in the Tokyo area are concerned, the highest priority is the consideration of the heat loss through the window system in winter. Replacement of a single pane to a double pane generally brings about a large decrease in heat loss but only a small decrease in solar heat gains. It is the other reason that we focused only on the heat loss through the windows in this article.

We estimated the heat loss by using the overall heat transmission coefficient (U-value) of the glazing and the frame and the degree-days in Tokyo. Table 1 shows the U-values of the three types of window systems. The degree-days of Tokyo are 1800°C × days, assuming that heating is required when the daily average of the outdoor air temperature is below 18°C and the desired room air temperature is 18°C. The amount of heat lost per one winter season

Table 1. U-values of the three types of window system

Type 1	glass, aluminum frame	7.0 W/m²K (8.0 W/K)
Type 2		4.3 W/m²K (5.2 W/K)
Type 3	wooden frame	3.1 W/m²K (3.7 W/K)

Glass part is 1.02m² and frame part is 0.18m². The figures in the bracket are the heat loss coefficient of the whole window area of 1.2m². The U-values of single pane and double panes are assumed to be 6.3 W/m²K and 3.2 W/m²K, respectively. The U-values of the frame is assumed to be 10.8 W/m²K in the case of aluminium and 2.3 W/m²K in the case of wood (ASHRAE, 1989).

through the window systems was calculated from the following equation:

$$H = 24 \times 3600 \times D\,(U_g\,S_g + U_f\,S_f) \qquad (1)$$

where H is the heat loss per one winter season through the window system [J/season], D is the degree day [°C × days], U is the overall heat transmission coefficient [W/m^{2}K], S is the surface area [m^2]. The subscripts, g and f, denote glass and frame, respectively. No ventilation was assumed.

We calculated the sum of the waste heat in

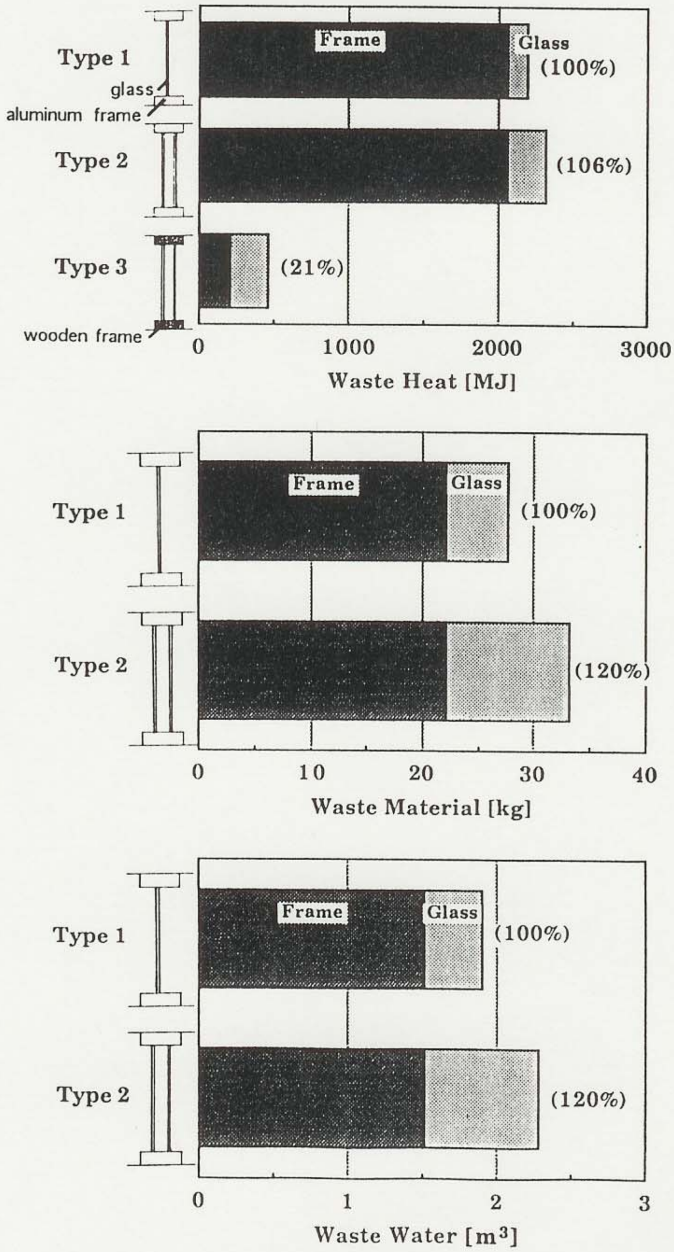

Fig. 4. Waste heat, waste material, and waste water by-produced when the three types of window system of 1.2 m^2 are produced.

the production process and the heat lost through the window systems from the following equation:

$$H_{sum} = H_p + n\,H \tag{2}$$

where H_{sum} is the sum of the waste heat in the production process and the heat lost through the window systems for a period to be evaluated [J]; H_p is the waste heat in the production of window systems [J] (see Fig. 4); n is number of winter seasons.

Figure 5 shows the sum of the waste heat dumped in the production process and the heat lost through the windows during the heating seasons among the above three types of window systems. As described in Section 3.3, Type 2 must dump a little more waste heat than Type 1 does as far as the production process is concerned, because the total area of the glass sheet doubles. But the heat loss coefficient of Type 2 is much smaller than that of Type 1, as shown in Table 1, so that the sum of the waste heat in

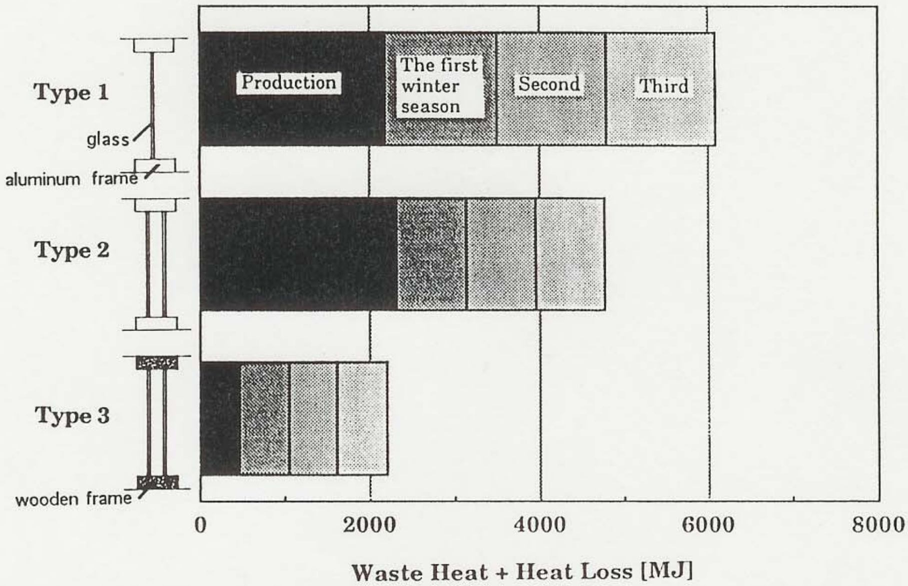

Fig. 5. Comparison of the waste heat in the production process and the heat lost through the three types of window system.

the production process and the heat loss through the window of Type 2 becomes smaller than that of Type 1 within the first winter season. This suggests that taking the environmental issues into consideration, the cost of double glazed windows in Japan should be lowered much more. The sum of the waste heat in the production process and the heat loss through the window over three winter seasons in the case of Type 3 is almost the same as the waste heat in the production process in the case of Types 1 and 2, because the wooden frame was assumed to dump a smaller amount of waste heat than the aluminum frame does in the production process. The wooden frame contributes also to reducing the heat loss because of the low thermal conductivity. Although the use of wooden frames is basically considered to be welcomed, we should also be concerned about where and at what rate we may get wooden materials so that we do not help accelerate deforestation.

4. CONCLUSION

We have investigated the production systems of a glass sheet and an aluminum frame in terms of inflows and outflows of energy and matter. The amounts of waste heat, waste materials, and waste water in producing 1 kg of aluminum frames are much greater than those in producing 1 kg of glass sheets. The sum of the waste heat and the heat loss in the case of a double glazed window becomes smaller than that in the case of a single glazed window within the first winter season in Tokyo.

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