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Research on Measurement and Calculation of Carbon Emission from the Production of Prefabricated Building Components

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Abstract: The measurement and calculation of the carbon emission from the production of prefabricated building components were studied. Based on the carbon emission factor method, a carbon emission calculation model of the components in the production phase was established. Besides, the actual measurement method and calculated at rated power method were proposed for the measurement and calculation of carbon emission, and several measurements were carried out in a component factory located in a coastal area of south China and a component factory located in Beijing, respectively. The results of the study show that the carbon emission factors of laminates and wallboards produced by factories located in coastal areas of southern China under natural curing conditions were 7.61 kg CO_2/m^3 and 5.84 kg CO_2/m^3 respectively. The carbon emissions conversion coefficients of concrete mixer, reinforcing bar production line and travelling crane between actual operation and with per the rated power were approximately 0.44, 0.34 and 0.34 respectively. When the actual measurement cannot be performed, the conversion coefficient can be used to correct the data of the calculated at rated power to make it closer to the true value. The carbon emission factor of the laminated panels produced by the component factory in Beijing under steam curing concrete conditions was 132.15 kg CO_2/m^3, and the factory is used as a prototype, a complementary steam generation system model of solar energy and boiler was established, and it was calculated that the system can reduce CO_2 emissions by about 300 tons throughout the year.

Key words: Prefabricated building, production, carbon emission calculation, carbon emission factor of components.

1. Introduction

In China, the construction industry, as one of the supporting industries of national economy, not only has been promoting the economic development, but also has been exerting huge influences on the environment. According to the statistics, the carbon emission from the construction industry accounted for 30% of the total in China [1]. In recent years, China has vigorously developed the prefabricated buildings for the object of accelerating the urbanization, and such buildings feature high productivity, short construction period, etc. However, there is a need to carry out measurement and calculation regarding whether such buildings can effectively reduce the carbon emission from the construction industry [2]. Domestic and foreign scholars measured and calculated the carbon emission on building carbon emissions based on the life cycle assessment method [3] and process analysis method [4]. The results showed that the carbon emission from the maintenance and demolition of the prefabricated buildings could be calculated with reference to the carbon emission calculation method suitable for the traditional cast-in-place buildings [5]. The production of the building components is unique to the prefabricated buildings, and is also a main stage when these buildings differ from the traditional cast-in-place buildings in the carbon emission [6]. However, the measurement and calculation of the carbon emission from the production of the prefabricated building components have rarely been studied, and a relatively uniform measurement and calculation method has not yet been formed. Therefore, in this paper, the carbon

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emissions from the production of the prefabricated building components were researched, and the carbon emission factors of the laminated panels and wall panels from a component factory located in a coastal area of south China were determined, thus providing a reference for the calculation of energy consumption and carbon emission from the production of the prefabricated building components. And based on a component production plant in Beijing, a model of a steam generation system with solar and boiler complementation was established to simulate the annual CO_2 emission reduction of the system, thus providing a reference for energy saving and emission reduction of assembled building component factories.

2. Method and Measurement

2.1 Calculation Boundary

The calculation boundary of energy consumption during the production phase of prefabricated building components [7] starts from the entry of raw materials into the factory and ends when the components are shipped out of the factory. During this period, the carbon emissions from the operation of all the equipment involved in production and transportation (including the production line, concrete mixer, trusses and gantry crane) all need to be calculated and counted.

2.2 Calculation Model

At present, three methods are mainly used to measure and calculate the carbon emission from the buildings: emission factor method [8], mass balance method [9] and field measurement method [10], among which the emission factor method is the most widely used. Taking the emission factor method as the basis, the calculation model for the carbon emission from the production of the components was built according to the actual production conditions:

$$Car = \sum_{i=1}^{n} W_i \tag{1}$$

Car is the carbon emission from the production of building components, kg CO_2;

W_i is the carbon emission from each production and processing stage, kg CO_2.

$$W_i = m \times T_i \times P_d \times e \tag{2}$$

or

$$W_i = m \times T_i \times P_y \times y \tag{3}$$

e is the carbon emission coefficient for electricity, kg CO_2/kW·h;

m is the number of machines used in the i^{th} production process;

T_i is the processing time of the i^{th} production process, h;

P_d is the rated power of the machine used in the i^{th} production process, kW;

y is the carbon emission coefficient for energy, mainly including coal, fuel oil and natural gas, kg CO_2/t, kg CO_2/L, kg CO_2/m^3;

P_y is the energy consumption of the i^{th} production process per unit time, t/h, L/h, m^3/h.

Eq. (2) is applicable to electrically-driven production processes. Eq. (3) is applicable to production processes driven by other energy, such as coal, fuel oil and gas.

2.3 Measurement Method

Two carbon emission measurement methods were proposed based on the carbon emission calculation model in this research.

2.3.1 Indirect Measurement Method

The indirect measurement method refers to that the relevant measuring equipment is used to measure the energy consumption by the production of the building components, and the carbon emission from the production is then calculated. This method can truly reflect the energy consumption of components in actual production, with fewer intermediate links and accurate results, but the measurement process requires a certain amount of human and material input.

2.3.2 Rated Power Method

When the factory can not provide the actual measurement conditions, the energy consumption and carbon emission calculation can be performed by the rated power method. In the actual production of the factory, the production equipment is operated at actual power, so the calculation results of this method have certain errors with the true values, and need to be corrected by the carbon emission conversion coefficient.

3. Results and Discussions

3.1 Production Carbon Emissions under Natural Curing

In order to obtain the carbon emission factor *C* of the building components (carbon emission from the production of the building components per unit volume, kg CO_2/m^3), several measurements were carried out in a component factory located in a coastal area of south China using the indirect measurement method. The component factory mainly produces laminated panels, wall panels, among many other building components, while the production lines in the workshop include automatic laminated panel production line, fixed wall panel production line and automatic reinforcing bar production line. The plant performs natural curing of concrete components.

The combination of MIK-D200 electric quantity recorder and open-close current transformer was used to measure the current, voltage and operating time of each equipment, and the schematic diagram for the layout of the measuring points is shown in Fig. 1.

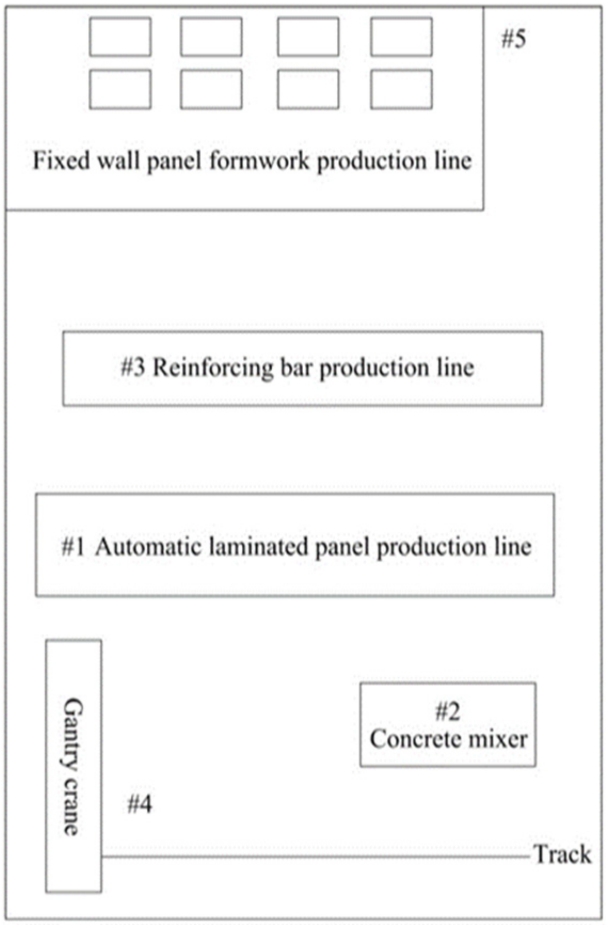

Fig. 1 Schematic diagram for layout of measuring points.

Where:

Measuring point #1 was used to measure the electricity consumption of the automatic laminated panel production line, of which the main consumers included sweeper, ferry bus, spraying machine, drawing machine, concrete spreader, vibrator, feeder and edge-on machine;

Measuring point #2 located at the concrete mixing station was used to measure the electricity consumption of the mixer;

Measuring point #3 was used to measure the electricity consumption of the reinforcing bar production line, of which the main consumers included integrated machine for reinforcing bar, reinforcing bar bending machine and reinforcing bar straightening machine;

Measuring points #4 and #5 were used to measure the electricity consumption for transportation in the factory; the measuring point #4 was used to measure the electricity consumption of the gantry crane on the south; the measuring point #5 was used to measure the electricity consumption of the transportation equipment used in the fixed wall panel formwork production line, mainly including truss, carrier vehicle and gantry crane.

Most of the production equipment is electricity-consuming equipment, and carbon emissions are mainly generated by electricity consumption. Therefore, the carbon emission factor is calculated as follows:

$$C = P_e \times \alpha_e \tag{4}$$

C is the carbon emission of a building component per unit volume, kg CO_2/m^3;

P_e is the electricity consumption from the production of the building component per unit volume, $kW \cdot h/m^3$;

α_e is the carbon emission factor of electric energy. It was taken to be 0.7035 kg $CO_2/kW \cdot h$ in this paper.

The electricity of the production of the building components was mainly consumed by the automatic production line, concrete mixer, reinforcing bar production line and intra-factory transportation equipment.

Where:

$$P_e = P_{e1} + P_{e2} + P_{e3} + P_{e4} \quad (5)$$

P_{e1} is the electricity consumption of the automatic production line for producing the building components per unit volume, $kW \cdot h/m^3$;

P_{e2} is the electricity consumption of the mixer for producing the building component per unit volume, $kW \cdot h/m^3$;

P_{e3} is the electricity consumption of the reinforcing bar production line for producing the reinforcing bar for the building components per unit volume, $kW \cdot h/m^3$;

P_{e4} is the electricity consumption for transporting the building components per unit volume, $kW \cdot h/m^3$.

Where:

$$P_{ej} = E_{ej}/V_j \quad (6)$$

P_{ej} is the electricity consumption from the j^{th} production process of a building component per unit volume, $kW \cdot h/m^3$;

E_{ej} is the electricity consumption from the j^{th} production process of a building component;

V_j is the concrete consumption required for the j^{th} production process of a building component, m^3.

Where:

$$E_{ej} = \frac{(I_{aj} + I_{bj} + I_{cj}) \times U \times T}{\sqrt{3}} \quad (7)$$

I_{aj}, I_{bj}, I_{cj} are the three-phase current of the equipment used in the j^{th} production process, A;

U is the line voltage of the equipment, V;

T is a duration when the electricity recorder collects data, h;

$\cos\omega$ is power factor. It is generally taken to be 0.7-0.9.

According to the above formulae, the calculated carbon emission factors of the laminated panels and wall panels were 7.61 kg CO_2/m^3 and 5.84 kg CO_2/m^3 respectively. The calculated results are summarized in Table 1.

It can be seen from Table 1 that the fundamental reason for the difference in carbon emission from the production of the laminated panels and the wall panels lied in the carbon emission from the automatic production line. The wall panel is produced on a fixed formwork. Most of the electrical equipment is a truss. The carbon emissions per unit volume of wall production are about 30% less than the carbon emissions per unit volume of laminated panels produced by an automatic production line, but the work efficiency is lower than the automatic production line.

It also can be seen from Table 1 that the concrete mixing process is the production link with the largest proportion of carbon emissions in the production of laminated panels and wall panels (about 40% of total carbon emission from the production of laminated panels and about 50% of the total carbon emission from the production of wall panels). Therefore, the concrete mixer presented the highest potential in reducing the carbon emission.

The daily concrete output of a concrete mixer for 5 consecutive days was recorded, and the total

Table 1 Carbon emission factors of laminated panels and wall panels.

Production process	Laminated panels (kg CO_2/m^3)	Wall panels (kg CO_2/m^3)
Automatic production line	2.58	0.00
Concrete mixer	3.06	3.06
Reinforcing bar production line	1.22	0.94
Intra-factory transportation	0.75	1.84
C	7.61	5.84

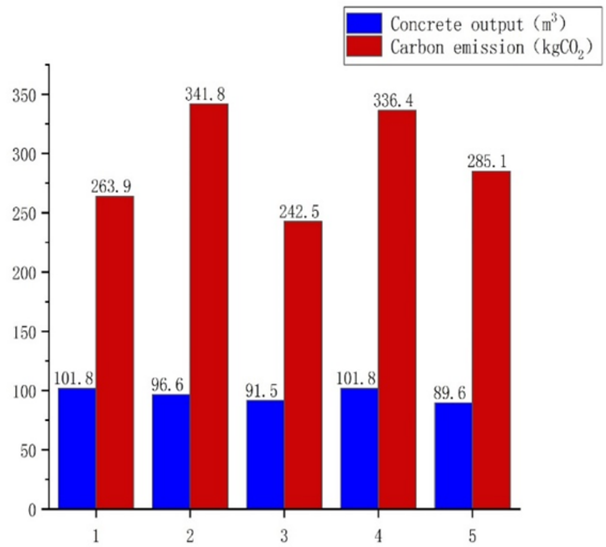

Fig. 2 Data comparison for daily output and carbon emission of concrete mixer.

daily carbon emission was calculated, as summarized in Fig. 2.

It can be seen from Fig. 2 that the daily output of the concrete mixer was not linearly associated with the corresponding carbon emission. The carbon emission did not increase with concrete output. The concrete output on day 1 was equal to that on day 4, but the carbon emission on day 4 was about 70 kg more than that on day 1. The main reason for this difference is that the operation time of the concrete mixer on the fourth day is more than the first day. Therefore, under the condition that the concrete consumption is satisfied, the reduction of the concrete mixer's operation time as far as possible can effectively reduce the carbon emission.

Carbon emission conversion coefficient of the main production equipment was calculated. Taking a concrete mixer as an example, it operated from 7:00 a.m. to 16:00 p.m. (of which the lunch break was from 11:00 a.m. to 12:00 a.m.). The average value of the carbon emissions released by the concrete mixer at the actual power and at the rated power for five consecutive days is calculated respectively. The carbon emission at the actual power is 294 kg CO_2, the carbon emission at the rated power is 670 kg CO_2, the carbon emission at the actual power is about 44% of the carbon emission at the rated power, so the carbon emission conversion factor of the concrete mixer is 0.44. Similarly, the carbon emission conversion coefficient of both the reinforcing bar production line and the truss was approximately 0.34.

3.2 Production Carbon Emissions under Steam Curing

A component factory in Beijing was used to measure and research carbon emissions using the same method. Beijing is a cold area, and gas-fired boilers are opened throughout the year to produce steam for steam curing components. The calculated results are summarized in Table 2.

As can be seen from Table 2, the carbon emissions generated by the steam curing process account for 90% of the total carbon emissions generated by the plant's production of laminated panels. The carbon emissions of concrete mixers and automatic production lines account for a small proportion of the total carbon emissions. Therefore, the energy conservation and emission reduction potential of the steam curing link in the production process of components is the largest.

In the steam curing system, high-temperature steam is generated by gas-fired boilers. Since the curing warehouse is basically in operation all year round, this will inevitably lead to a large amount of natural gas being consumed and a large amount of carbon emissions being generated. If renewable energy can be introduced into the steam curing system as a supplementary energy to the curing system, it will inevitably reduce the carbon emissions of the steam curing [11].

According to the actual situation of the factory, solar energy can be introduced into the steam curing

Table 2 Carbon emission factors of laminated panels.

Production process	Laminated panels ($kg\ CO_2/m^3$)
Concrete mixer	5.25
Automatic production line	6.63
Steam curing	120.27
C	132.15

system, and a steam generation system complementary to solar energy and boilers can be established. The liquid water in the vacuum tube is heated to the saturated state by the solar collector and then passed into the hydrophobic expansion container; in the hydrophobic expansion container, part of the saturated water is vaporized by means of pressure reduction to obtain saturated steam. The remaining part of the water will be cooled to the saturation temperature of the current pressure, and then re-entered into the solar collector by the circulation pump. When the steam produced by solar energy can not meet the steam load required by the steam curing system, additional steam is provided by the gas boiler to ensure the normal operation of the curing system. The system diagram is shown in Fig. 3.

The use of solar energy and boiler complementary steam generation system and the use of only gas-fired boilers to produce steam to reduce carbon emissions are simulated by Matlab software. The calculation results are shown in Fig. 4.

It can be seen from Fig. 4 that the steam generation system where solar energy and boilers are complementary has a significant CO_2 emission reduction effect, which can reduce carbon emissions by about 300 tons throughout the year, but the emission reduction is affected by the season. The emission reduction in summer is about twice that in winter. This is because the solar radiation intensity in summer and the duration of sunshine are greater than in winter, so that the amount of steam produced by solar energy in summer is more than that in winter, and from the heat transfer theory analysis: the average temperature in summer is higher than that in winter, making the heat loss of the summer steam curing system less than winter, so summer production energy consumption and total carbon emissions are less than winter. However, the CO_2 emission reduction throughout the winter can still reach about 50 tons. Therefore, it can be seen that the introduction of solar energy in the steam curing system has a very

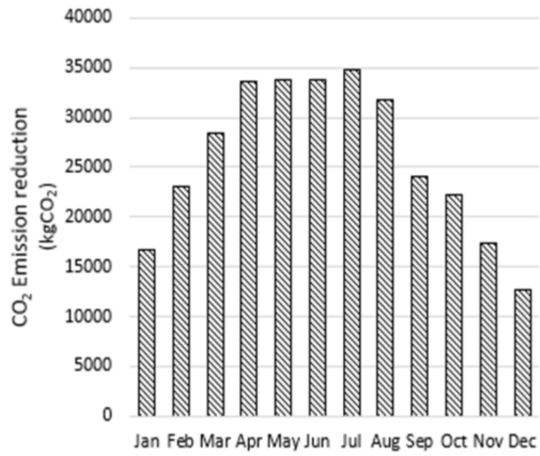

Fig. 3 Solar and boiler complementary steam generation system.

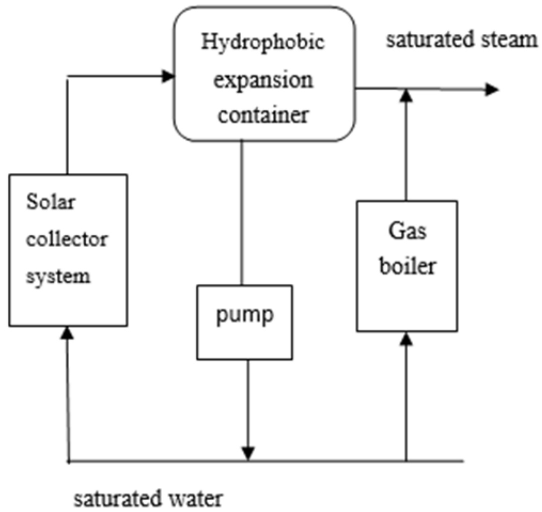

Fig. 4 The annual carbon emission reduction of the solar and boiler complementary steam generation system.

significant effect on the emission reduction effect of the curing system of the prefabricated building components factory.

4. Conclusions

The calculation and measurement of the carbon emission from the production of the prefabricated building components were studied, and obtained the following conclusions:

(1) The carbon emission calculation model of prefabricated building components at the production stage was established, and two methods of measuring carbon emissions by indirect measurement method

and rated power method were proposed.

(2) Under natural curing conditions, the carbon emission factors for laminated panels and wall panels produced by a component factory along the coast of southern China were calculated to be 7.61 kg CO_2/m^3 and 5.84 kg CO_2/m^3, respectively.

(3) Under natural curing conditions, the carbon emission from the concrete mixer was the largest during the production of laminated panels and wall panels. The operating time of the concrete mixer was a main factor affecting the carbon emission of the concrete mixer. When the concrete consumption conditions were met, the carbon emission can be effectively reduced by minimizing the operating time of the concrete mixer.

(4) The carbon emission from all kinds of equipment calculated by the rated power method needed to be corrected based on the carbon emission conversion coefficient. Through calculation, the conversion coefficients of the concrete mixer, reinforcing bar production and truss were approximately 0.44, 0.34 and 0.34 respectively.

(5) The concrete steam curing link has huge emission reduction potential. The introduction of solar and boiler complementary steam generation systems can reduce carbon emissions by about 300 tons throughout the year. However, the amount of CO_2 emission reduction is affected by seasonality, and the amount of emission reduction in summer is about twice that in winter.

Acknowledgments

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