Research on Economic Balance Point of Air Source Heat Pump Based on Load Characteristics of Teaching Building

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Abstract. In recent years, as the country pays more and more attention to clean heating, the application of air source heat pumps is growing rapidly. However, air source heat pumps have not been widely used for heating teaching buildings in the bitterly cold areas in the north. The determination of the economic balance point temperature of the air source heat pump has an important impact on the system capacity, initial investment and operating costs. This paper took Shenyang City, Liaoning Province as an example, of the meteorological conditions and electricity price policy in the heating season, combined with the heat load characteristics of the teaching building, and used DeST software to calculate the building heat load of the teaching building. The air source heat pump coupled electromagnetic energy heating system was selected as the heat source, and then used the TRNSYS software to establish the coupled system model. Finally, the optimal economic balance point temperature was calculated and analyzed by using the annual value of cost method. The results demonstrate that the optimal economic balance point temperature of the air source heat pump coupled electromagnetic energy heating system in this teaching building is -6℃. Meanwhile, compare with the single air source heat pump heating system, the initial investment and annual value of the cost of the coupled heating system are reduced by 23.1% and 9.9%. The air source heat pump coupled with electromagnetic energy heating system based on the optimal economic balance point temperature has a good applicability in school building construction in bitterly cold regions.

Keywords: bitterly cold region; air source heat pump; balance point temperature

1 Introduction

Air source heat pumps use the principle of inverse Carnot cycle to convert low-grade heat in the air into high-grade heat, due to its value endless, clean, efficient and other advantages, in recent years has been widely used in heating. However, the air source heat pump has a significant disadvantage: In the winter, as the outdoor temperature decreases, the building heat load rises, and the air source heat pump heating capacity

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gradually declines. For this reason, it is often necessary to include an auxiliary heat source when using air source heat pump for heating. The air source heat pump and auxiliary heat source need to be selected according to the economic balance point temperature. When the economic balance point temperature is higher, the air source heat pump is smaller, the auxiliary heat source is larger, the initial investment and operating costs are lower, but it will lead to the inability to play well with the advantages of the air source heat pump; when the economic balance point temperature is lower, the air source heat pump is larger, the auxiliary heat source is smaller, the initial investment and operating costs are higher, and at the same time, due to the long term of air source heat pump operating under part-load conditions, resulting in a decrease in the coefficient of performance. It can be seen that the selection of economic balance temperature plays a significant role in the initial investment and operating costs of the system. Selecting the appropriate economic equilibrium point temperature means that from the perspective of the whole system, the initial investment in the system can be reduced while reducing the operating costs of the system. Therefore, determining the optimal economic balance point temperature of air source heat pumps is crucial to improving the economy of the heating system.

Jiang Yiqiang et al. were the first to put forward the concept and mathematical model of economic balance point temperature in China, and gave the optimal economic balance point temperature of several typical areas according to the arithmetic example[1]. Sun Mei et al. rural schools in the north of China as an example, compared with coal-fired boiler heating, introduced the advantages of electric heating and heating materials[2]. Li Qun to the Xinjiang region as an example, the electric boiler coupled air source heat pump thermal storage heating system and a single electric boiler heating system for comparative analysis, found that the coupled system in the economy and environmental benefits of both are better than a single electric boiler heating system[3]. Feng Guohui et al. took a residential building in Shenyang as an example, compared and analyzed the air-source heat pump coupled electromagnetic energy heating system with a single air-source heat pump heating system and a single electromagnetic energy heating system, and found that the operation of the coupled system was more stable. The system was better in terms of environmental benefits, and the indoor thermal comfort was higher[4]. Wang Shaorui studied the balance point temperature of the air source heat pump coupled heating system with low valley electricity as an auxiliary heat source by taking Urumqi as an example[5]. Li Hao et al. studied the break-even point of the coupled heating system of air source heat pump and gas boiler by taking the actual heating project in Langfang as an example, and gave the optimal configuration of the system[6]. Yang Lingyan et al. analyzed the performance balance point temperature and economic balance point temperature of low-temperature and conventional air source heat pumps applied in different buildings, and gave the optimal performance balance point and optimal economic balance point for different regions and types of buildings[7]. Bagarella et al. conducted a study on the coupled heating system composed of air source heat pumps and electric boilers or gas boilers, and analyzed the optimal balance point temperature for the use of coupled heat pump systems under different climatic conditions[8]. Matteo et al. investigated the effect of the minimum operating temperature of the heat pump and the balance point temperature on the seasonal performance of the system, and concluded that the operating efficiency of the heat pump increases when the minimum operating temperature of the heat pump is between the balance point temperature and the outdoor design temperature of the heating plant[9].

From the above study, it was found that the optimal economic balance point temperature is categorized into two types of methods for determining the annual value of cost method and the whole life cycle cost. Most of the domestic studies have focused on the determination of the optimal economic balance point temperature, and most of the foreign studies have focused on the determination of the capacity of the units in the coupled system. Meanwhile, there are fewer analyses of the optimal economic balance point temperature of school building construction in bitterly cold regions. This paper took a teaching building in Shenyang as an example, used DeST software to analyze its heating season heat load, then used TRNSYS software to build a single air source heat pump heating system and air source heat pump coupled with electromagnetic energy heating system model, finally called the GENOPT module in TRNSYS software to take the annual value of the system's cost as the optimization objective, and the Hooke-Jeeves algorithm was used to analyze the optimal economic balance point temperature of the air source heat pump that meets the heat load characteristics of the school building in the cold region.

2 Analysis of the Study Population

2.1 Meteorological Parameters

The research object of this paper is located in Shenyang City, Liaoning Province (46.717°N, 123.433°E), which is located in the south of northeastern China. The outdoor meteorological parameters used in this paper are the typical annual meteorological parameter data of Shenyang city from TRNSYS software, and the outdoor temperature changes in Shenyang throughout the year are shown in Figure 1.

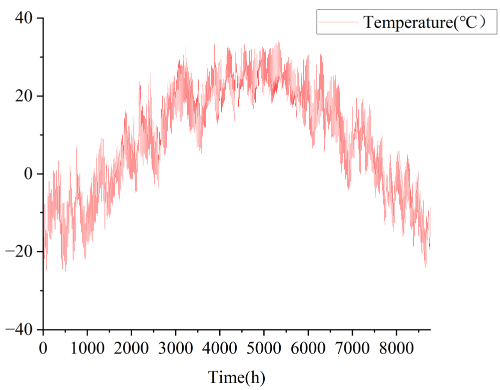

Fig. 1. Year-round change of outdoor temperature in Shenyang

As can be seen from Figure 1, the average annual temperature of Shenyang is 8.58 °C, the lowest temperature of the year is -25.3 °C, the coldest month is January, and the average temperature is -11.6 °C. According to Shenyang city's heating policy regulations, Shenyang city's heating period is from 0:00 on November 1 to 24:00 on March 31 of the following year, a total of 150 days, the total duration is 3624h. The maximum temperature of the heating season is 17.85 °C, the minimum temperature is -25.3 °C.

2.2 Building Heat Load Calculation

Shenyang city in the thermal design area belongs to the bitterly cold C area. This paper takes the teaching building as the object of study, the building is north-south direction, has a total of four floors, each floor height is 3m, the east-west length is 47.7m, the north-south length is 8.92m, the total floor area is 1552 square meters, the teaching building 1-4 layers of the floor plan schematic diagram are shown in Figure 2 and Figure 3.

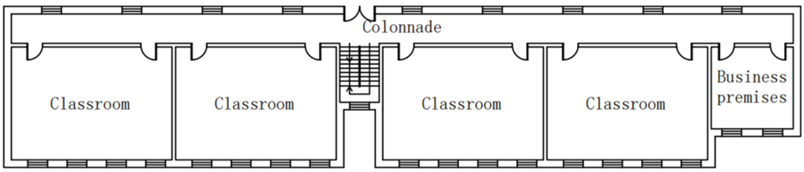

Fig. 2. Architectural plan of the first floor of the school building

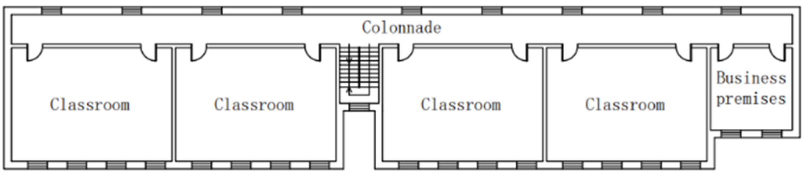

Fig. 3. Architectural plan of the 2-4 floors of the school building

The teaching building is modeled by using DeST software, and the DeST software building model is shown in Figure 4.

According to the relevant provisions in the *General Specification for Building Energy Efficiency and Renewable Energy Utilization (GB55015-2021)*[10], the main parameters of the building are set in the DeST software. The building envelope parameters are set as shown in Table 1. The simulation results of time-by-time heat load and load factor during the heating season are shown in Figure 5.

The simulation results show that the maximum heat load of the teaching building in the heating season is 196.2kW, and the cumulative heat load in the heating season is 45126.93kW·h, and the cumulative heat load index for the whole year is 29.08kW·h/m^2. At the same time, due to the fact that indoor heating at night and during the holiday time of the heating season only requires a duty temperature of 5°C, which makes the heat load of the building very small, resulting in a heat load that is less than 20% of the design heat load for 78% of the total time, and heat load that is greater than 80% of the design heat load for 10.3% of the total time. Therefore, for the teaching building, if the air source heat pump is used separately for heating, it will lead to the air source heat pump running at part-load conditions most of the time, which will reduce the energy-saving effect of the air source heat pump and also reduce the economy of the air source heat pump. Therefore, for the construction of the teaching building, it is crucial to choose the appropriate balance point temperature and reasonably allocate the heat load borne by the heat source to avoid unnecessary waste of resources.

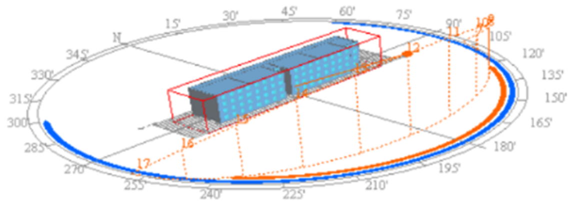

Fig. 4. Schematic of DeST building model

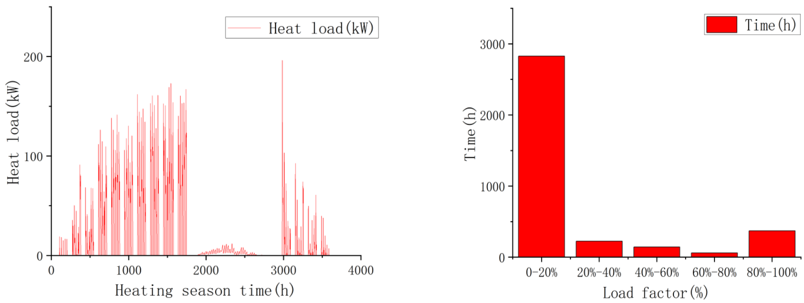

Fig. 5. Hour-by-hour heat load and load factor statistics for the heating season

Table 1. Enclosure parameters

Envelope	Heat transfer coefficient (W/m^2·K)
External wall	0.337
Interior wall	1.68
Floor	2.925
Roof	0.238
Window	2.7

3 TRNSYS Simulation System Construction

3.1 Modelling of Individual Air Source Heat Pump Heating

Use TRNSYS software to establish the simulation diagram of individual air source heat pump heating, the system diagram is shown in Figure 6. And according to the system heat load of the system parameters are set, the system components parameters set as shown in Table 2. At this time, the total energy consumption of the system for the whole heating season is 29165kW·h.

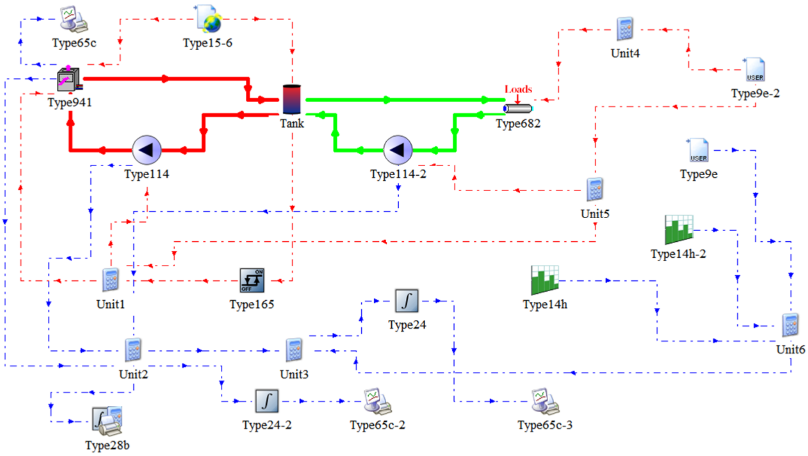

Fig. 6. Simulation model of air source heat pump heating system

Table 2. Parameter setting of individual air source heat pump heating system components

Part Name	Parametric	Value	Unit
ASHP	Rated heat capacity	130	kW
	Rating	65	kW
Tank	Capacity	14	m^3
	Heat loss coefficient	0.2	$kJ/h{\cdot}m^2{\cdot}K$
Circulating water pump	Rated flow rate	6.2	m^3/h
	Rating	1.3	kW

3. 2 Simulation Modelling of Air Source Heat Pump Coupled with Electromagnetic Energy Heating System

In this paper, electromagnetic heaters are selected as the auxiliary heat source of the air source heat pump. The operation mode of the coupling system is developed: At the beginning and the end of the heating season, the outdoor air temperature is high, the building heat load is small, and the air source heat pump has high energy efficiency, and at this time, the air source heat pump can satisfy the heating demand by running independently; in the middle of the heating period, the outdoor air temperature is low, the heating capacity of air source heat pump is lowered with the lowering of the outdoor air temperature, and the building heat load is increased with the lowering of the outdoor air temperature. When the outdoor air temperature drops below the equilibrium temperature, the air source heat pump running alone cannot satisfy the heating demand well, and the electromagnetic heater is started to make up the heat of the system.

The coupling system controls the start and stop of the heating system by monitoring the outlet water temperature at the end of the heat storage tank. The set temperature of the system heating is 45°C, and the temperature difference between supply and return water is 5°C. When the temperature at the top of the water tank is higher than 50°C, the air source heat pump, electromagnetic heater and heat pump side circulation pump are closed; when the temperature at the top of the water tank is reduced to 40°C, the heat pump side circulation pump and air source heat pump are opened, and if the outdoor temperature is higher than the balance point temperature at this time, only the air source heat pump is activated to heat the circulating water; if the outdoor temperature is lower than the balance point temperature, the air source heat pump and electromagnetic heater series operation, circulating water through the air source heat pump heating, and then flow through the electromagnetic heater for further heating, and finally flow into the heat storage water tank. Use TRNSYS software to establish the air source heat pump coupled with the electromagnetic energy heating simulation system shown in Figure 7.

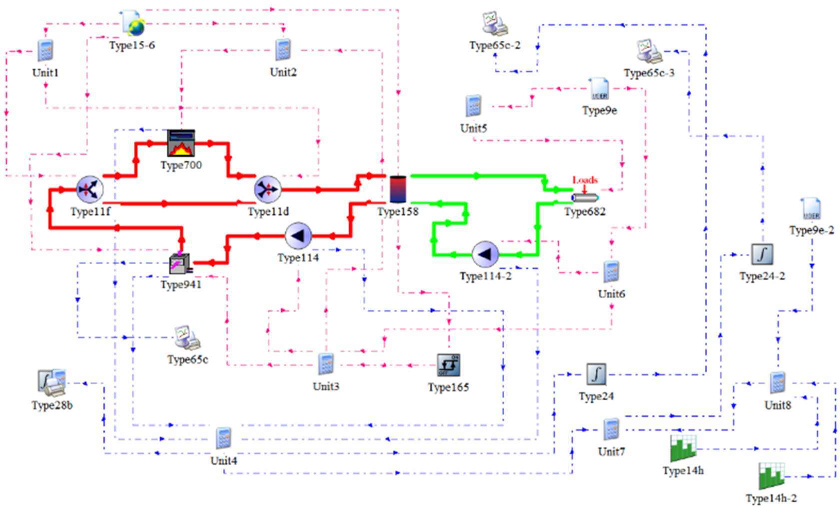

Fig. 7. Simulation diagram of air source heat pump coupled electromagnetic heater system

3.3 Initial Parameter Setting

The equilibrium temperature of the air source heat pump is closely related to the local meteorological conditions, and when different balance point temperatures are selected, the proportion of time that the air source heat pump operates alone and requires auxiliary heating and the proportion of time in which auxiliary heat sources are required to make up for the heat, and the proportion of time in which the trough electricity time accounts for the time that the auxiliary heat sources make up for the heat are shown in Figure 8. As can be seen from the figure, since the system uses an auxiliary heat source to make up heat below the equilibrium point temperature, the proportion of time taken up by the auxiliary heat supply increases as the equilibrium point temperature increases, and the proportion of time taken up by the air source heat pump to supply heat alone decreases. According to the tariff policy of Shenyang Development and Reform Commission, the tariff of Shenyang city is divided into the following: daily electricity consumption is divided into peak hours: 07:30-10:30, 16:00-21:00; weekday hours: 05:00-07:30, 10:30-11:30, 12:30-16:00, 21:00-22:00; low hours: 11:30-12:30, 22:00-05:00. The peak hours are 17:00-19:00 daily in winter (November and December), and the peak tariff will be implemented. The tariff ratio of peak, peak, usual, and valley hours is 1.875: 1.5: 1: 0.5. In order to make full use of the advantage of low tariffs in the valley hours, the initial balance point temperature of the system is selected to be -10°C. At this time, the time when the air source heat pump operates alone accounts for 74.5% of the total time of the heating season, and the time when the auxiliary heat source is needed for supplemental heating accounts for 25.5% of the total time of the heating season, of which the low valley electricity time accounts for 42.5% of the time when auxiliary heating is needed, and the results of selecting the components in the system based on the initially selected equilibrium temperature are shown in Table 3.

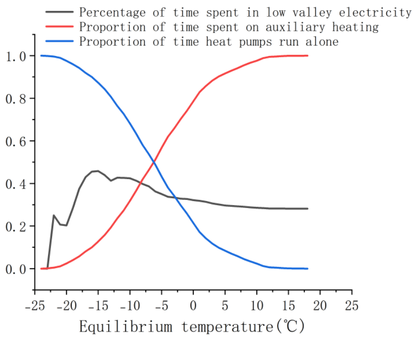

Fig. 8. Plot of equilibrium point temperature versus heating of system components

Table 3. Initial system parameter settings

Part Name	Parametric	Value	Unit
ASHP	Rated heat capacity	107.5	kW
	Rating	53.5	kW
Electromagnetic heater	Rating	15	kW
	Heating efficiency	90	%
Tank	Capacity	13.75	m^3
	Heat loss coefficient	0.2	kJ/h·m^2·K
Circulating water pump	Rated flow rate	5.1	m^3/h
	Rating	1.1	kW

The cumulative energy consumption of the coupling system is calculated to be 28609kW·h, the cumulative energy consumption of the air source heat pump unit to be 25175kW·h, and the cumulative energy consumption of the electromagnetic heater to be 1027kW·h throughout the heating season.

3.4 Optimal Economic Balance Point Temperature Calculation

The optimal economic balance point temperature means that if the capacity of the air source heat pump and auxiliary heat source in the system is determined according to this balance point temperature, it can ensure that the whole heating system, will have the lowest initial investment and operation cost. At present, there are two methods for determining the optimal economic balance point temperature, respectively, the annual value of the cost method and the whole life cycle cost. The two methods determine the optimal economic balance point temperature when the objective function is the same, the difference between the two is that the annual value of the cost method is the initial investment in the system according to the system's operating years of the year-by-year discount rate discounting, to get each year's initial investment discounted cost and operating costs; full life cycle cost is in the system's operating years of the initial investment and operating costs. The whole life cost is the annual operating cost of the system over the operating life of the system discounted to the value at the time of the initial investment, getting in the system’s operating life of the total cash value. Both are in the same parameters when the change rule is basically the same, this paper uses the cost of the annual value as the objective function to determine the optimal economic balance point temperature of the heating system. The initial investment in each component of the system is shown in Table 4.

Table 4. Initial investment table for major system components

Part Name	Cost	Unit
ASHP	1200	Yuan/kW
Electromagnetic heater	400	Yuan/kW
Tank	800	Yuan/m^3
Circulating water pump	500	Yuan/Unit

Use the GENOPT model in the TRNSYS software, the Hooke-Jeeves optimization algorithm is used for parameter optimization to ensure that the various configuration parameters in the system can be optimized synchronously, the optimization model is shown in Figure 9. And the optimized parameters of the coupled system are shown in Table 5.

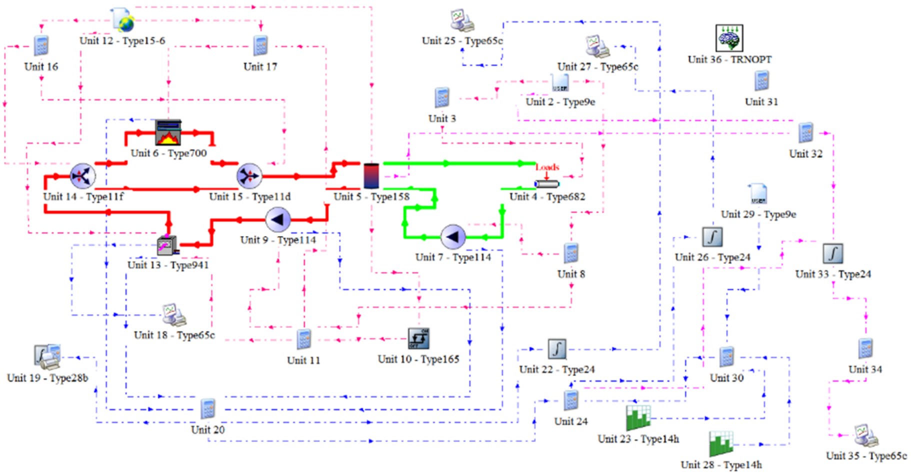

Fig. 9. Optimization models for coupled system

Table 5. Optimized system parameter settings

Part Name	Parametric	Value	Unit
ASHP	Rated heat capacity	92	kW
	Rating	46	kW
Electromagnetic heater	Rating	17	kW
	Heating efficiency	90	%
Tank	Capacity	14	m^3
	Heat loss coefficient	0.2	$kJ/h{\cdot}m^2{\cdot}K$
Circulating water pump	Rated flow rate	4.4	m^3/h
	Rating	0.9	kW
Equilibrium temperature		-6	℃

3.5 System Economic Analysis

The comparison of the economic indicators of the coupled system before and after optimization with the air source heat pump heating alone is shown in Table 6. From the table, it can be seen that the optimized system has an increase in temperature at the economic balance point relative to the pre-optimization system, resulting in a decrease in the capacity of the air source heat pump and an increase in the capacity of the electromagnetic heater, which increases the operating costs, but reduces the initial investment in the system due to a decrease in the capacity of the air source heat pump, resulting in a decrease in the annual value of the system costs. The coupled system compared to a single air source heat pump heating system in the initial investment and cost of the annual value of a significant reduction in the savings of 23.1% and 9.9%, respectively, has a better economic performance.

Table 6. Economy Comparison

Form	Individual air source heat pump heating	Pre-optimization	Post-optimization	Unit
ASHP	130	107.5	92	kW
Electromagnetic heater	0	15	17	kW
Tank	14	13.75	14	m^3
Equilibrium temperature		-10	-6	°C
Initial investment	168200	14700	129400	Yuan
Running cost	23600	23300	23400	Yuan
Annual value of cost	41400	39000	37300	Yuan

4 Conclusions

In this paper, based on the meteorological conditions and electricity price policy of Shenyang, combined with the heating characteristics of the teaching building, the model of air source heat pump coupled with electromagnetic heater heating system is constructed through the use of TRNSYS software, and the optimal economic equilibrium temperature of the building of the teaching building in Shenyang city is calculated to be -6°C; at the same time, the air source heat pump coupled with electromagnetic energy heating system saves the initial investment as compared with the single air source heat pump heating system, and the annual value of the cost is saved by 23.1%, the annual value of the cost savings of 9.9%, has a good economy. This study calculates and analyzes the optimal economic equilibrium point temperature of air source heat pump coupled with electromagnetic heater heating system, which helps to promote the use of air source heat pump coupled heating systems in cold regions. For the air source heat pump coupled with other kinds of heat source heating systems, it is also necessary to carry out a special calculation of the optimal economic balance point temperature, and it is not appropriate to use the conclusions of this study.

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