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An Energy-saving Aerodynamic Layout for Large-scale Conventional Hypersonic Wind Tunnel

Tiejin Wang

Abstract

The conventional hypersonic wind tunnel plays an important role in the design of hypersonic vehicles, where the pressure pure air is used as working medium, and heated through convection heaters. With the development of hypersonic vehicles, especially the vehicle with SCRAM jet as propulsion system, the large-scale conventional hypersonic wind tunnel with nozzle exit diameter of 2m order of magnitude is required, and its test capability will be extended from the conventional aerodynamic force and aero-heating tests to the thermal protection and Scramjet tests with high total temperature, for example, in the Scramjet tests to simulate the flow conditions of Mach number of 6, the total temperature may be about 2000K. The critical issue encountered in the design of this kind of large-scale conventional hypersonic wind tunnel is that the energy consumption, as well as the pollution of noise and waste heat of the exhausting working air, also increases dramatically in the tunnel operation with high temperature. How to save energy and decrease environmental pollution while the simulation conditions for the development of hypersonic vehicles are satisfied has become an important problem to be considered in the design of the conventional hypersonic wind tunnel. To solve the problem, the aerodynamic layout of the conventional hypersonic wind tunnel is optimized in this paper as follows: first, the aerodynamic layouts of the existing conventional hypersonic wind tunnels are summarized; second, the energy transformation in the conventional hypersonic wind tunnel during its operation is theoretically analyzed, and on the view of point of saving energy and protecting environment are also analyzed the methods used to deal with the exhausting working air in different aerodynamic layouts; third, the possible methods for utilizing the remainder energy of exhausting working air are discussed; finally, an optimized aerodynamic layout for the large-scale conventional hypersonic wind tunnel is put forward, and critical technologies to be used in the realization of the layout are discussed. The result of a simple calculation of saved energy in the optimized aerodynamic layout at typical run condition shows its advantages in saving energy and protecting environment.

Keywords: *hypersonic wind tunnel energy aerodynamic layout*

1. Introduction

The conventional hypersonic wind tunnel, a necessary testing facility for hypersonic vehicles, is a kind of hypersonic wind tunnel with pure air as working medium heated by convective heater transfer. In the 1950s, this kind of wind tunnels was built for the development of hypersonic vehicles, and since then, it has been innovated and built with much larger scale. For instance, the conventional hypersonic wind tunnel with nozzle exit size of 200~300mm in the order of magnitude was first built, which is mainly used to testify the aerodynamic characters of the simple configuration, such as war head and so on; then, the tunnel with nozzle exit size of 500~700mm, the aerodynamic characters of the configurations with the convex on their surfaces; up to now, the tunnel with nozzle exit size of 1000~1200mm has been building, the aerodynamic characters of the complex configurations, such as space shuttle and so on[1] [2] ; the tunnel with nozzle exit size of 2400~3000mm has been required in the development of hypersonic vehicles at present and will be built in the near future[3].

The development of the conventional hypersonic wind tunnel, on the one hand, is shown by the increasing size of nozzle exit, on the other hand, is also shown by the increasing capability of test

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simulation. In the future in the conventional hypersonic wind tunnel will not only the common tests of aerodynamic force and heating still be performed, but the tests for hot structure and SCRAM jet also conducted. The total temperature will reach about 2000K, which is near the total temperature of SCRAM jet in flight at Mach numbers of 6 and 7[4].

The energy consumption during the operation, however, increases greatly with the increasing size and total temperature of the conventional hypersonic wind tunnels, meanwhile, the pollution of waste heat and noise exhausted with the working air from the tunnels also causes an increasing influence on the local environment.

How to save energy and decrease environmental pollution while the simulation conditions for the development of hypersonic vehicles are satisfied has become an important problem to be considered in the design of the conventional hypersonic wind tunnel. To solve the problem, the aerodynamic layout of the conventional hypersonic wind tunnel is optimized in this paper as follows: first, the aerodynamic layouts of the existing conventional hypersonic wind tunnels are summarized; second, the energy transformation in the conventional hypersonic wind tunnel during its operation is theoretically analyzed, and on the view of point of saving energy and protecting environment are also analyzed the methods used to deal with the exhausting working air in different aerodynamic layouts; third, the possible methods for utilizing the remainder energy of exhausting working air are discussed; finally, an optimized aerodynamic layout for the large-scale conventional hypersonic wind tunnel is put forward, and critical technologies to be used in the realization of the layout are discussed.

2. Aerodynamic layouts of existing conventional hypersonic wind tunnels and their features

Based on the run type of conventional hypersonic wind tunnels, their aerodynamic layouts can be classified into three types: intermittent type, continuous type and intermittent & continuous type, which are all adopted in the existing tunnels and have their own features. The intermittent type is broadly used in most conventional hypersonic wind tunnels; the continuous type is typically used in the B and C wind tunnels in the AEDC of USA[5][6]; the intermittent & continuous type can be seen in the 1251A tunnel in Langley Research center of USA. The following are the specific aerodynamic layouts of conventional hypersonic wind tunnels [7] [8].

2.1. Intermittent type aerodynamic layout

There are also three types of aerodynamic layout in the intermittent one: injector type, vacuum type, and injector &vacuum type. The typical injector type and vacuum type aerodynamic layouts are shown in the Figure1 and Figure2. The injector &vacuum type aerodynamic layout is shown in Figure3.

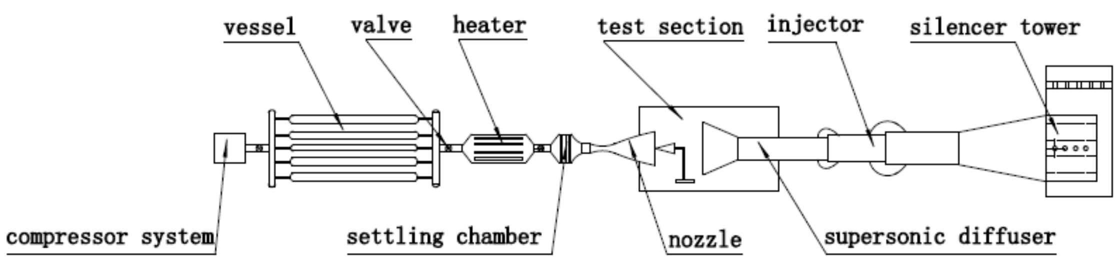

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Fig 1. Injector type intermittent aerodynamic layout of conventional hypersonic wind tunnel

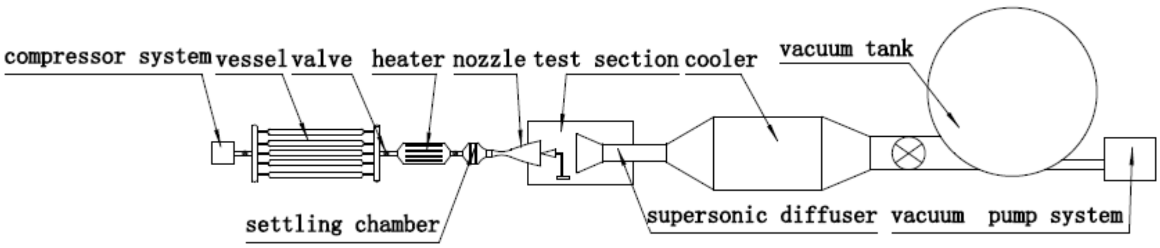

Fig 2. Vacuum type intermittent aerodynamic layout of conventional hypersonic wind tunnel

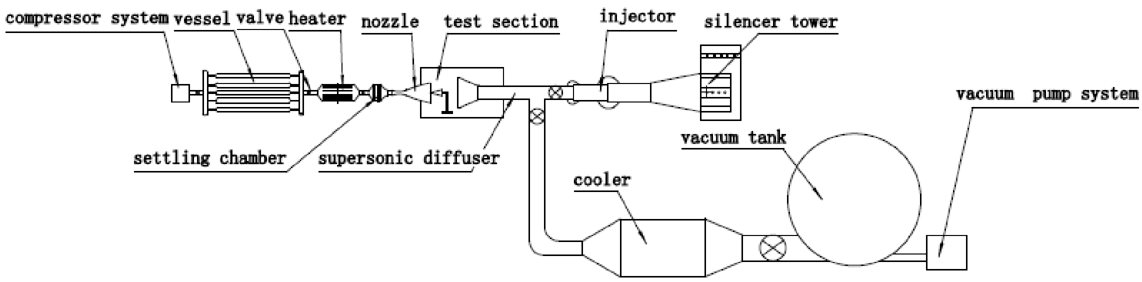

Fig 3. Injector &vacuum type intermittent aerodynamic layout of conventional hypersonic wind tunnel

In the intermittent type conventional hypersonic wind tunnel, the air flow from tanks with pressure air, reaches the needed total temperature after heaters, and forms the needed hypersonic flow field in the test section after passing through a contour nozzle, then through the supersonic diffuser, the air flow enters the injector system and is exhausted into atmosphere; or, through the cooler, it enters the vacuum system and is exhausted into atmosphere.

The run features of the intermittent type conventional hypersonic wind tunnel are as follows: first, the air flow after finishing its function in the test section isn't reclaimed; second, the needed power to run the tunnel is far less than the running power of the tunnel.

2.2. Continuous type aerodynamic layout

The typical continuous type aerodynamic layouts are shown in the Figure4.

In the continuous type conventional hypersonic wind tunnel, the air flow in a closed pipe circuit first pressured by air compressors, reaches the needed total temperature after heaters, and forms the needed hypersonic flow field in the test section after passing through a contour nozzle, then through the supersonic diffuser, it enters the vacuum system after passing a cooler, and is exhausted into air compressors for another circulation.

The run features of the continuous type conventional hypersonic wind tunnel are as follows: first, the air flow after finishing its function in the test section is reclaimed with no air flow exhausted into atmosphere; second, the needed power to run the tunnel is same as the running power of the tunnel.

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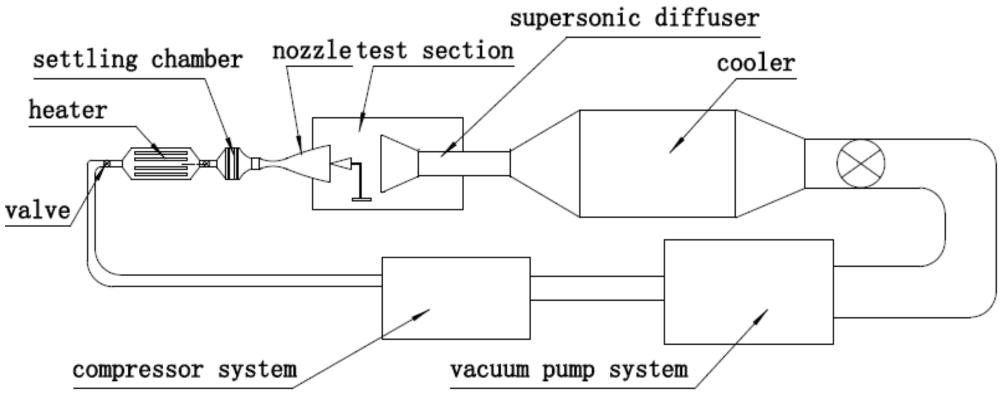

Fig 4. Continuous aerodynamic layout of conventional hypersonic wind tunnel

2.3. Intermittent &Continuous aerodynamic layout

The intermittent &Continuous type conventional hypersonic wind tunnel combines the characters of the intermittent type and continuous type tunnels, which can be used to much larger Mach number and Reynolds number ranges.

This type of aerodynamic layout was used in the 1251Awind tunnel in Langley research center, shown in Figure5.

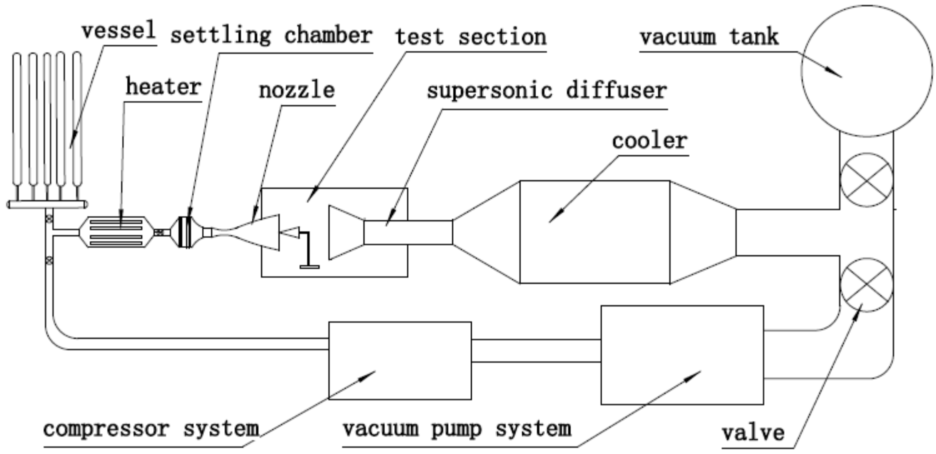

Fig 5. Intermittent &continuous structure layout of conventional hypersonic wind tunnel

Through the opening and closing of the valves in corresponding branch pipes, the intermittent &Continuous type conventional hypersonic wind tunnel can be operated as an intermittent type tunnel or as a continuous type tunnel.

The run features of the intermittent &Continuous type conventional hypersonic wind tunnel are as follows: first, the compressor system and the vacuum system can be commonly used by the two types of aerodynamic layouts; second, the needed power to run the tunnel is same as the running power of the tunnel.

3. Analysis on energy change in existing conventional hypersonic wind tunnels

3.1. Intermittent &Continuous aerodynamic layout

During the operation of a conventional hypersonic wind tunnel, whether are there some kinds of energy to be saved? The solution to the problem can be obtained through the analysis of the course of energy change in the conventional hypersonic wind tunnel.

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According to the theories of compressible aerodynamics, the flow in the conventional hypersonic wind tunnel can be approximately analyzed by one-dimensional theory, where the air flow with a certain flux to form the flow field of needed Mach number at the exit of nozzle of a conventional hypersonic wind tunnel is increased two kinds of energy, pressure energy and heat energy, from the compressor system and the heater system, respectively, as shown in Figure 6.

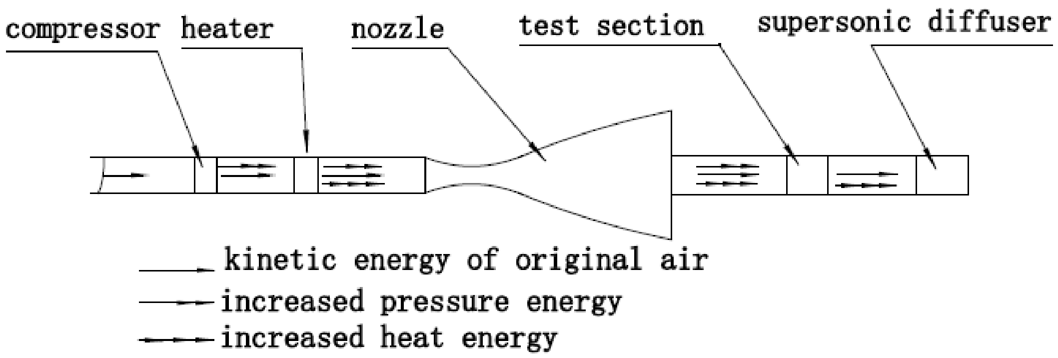

Fig 6. Energy change in conventional hypersonic wind tunnel

After the air flow passes the nozzle, the most of two kinds of the increased energy is turned into the kinetic energy of the air flow. Based on the hypothesis in the one-dimensional theory that the air flow passing through the nozzle is an iso-entropy flow, the total energy of the air flow into the nozzle is equal to the one of the air flow out the nozzle, and the nozzle only acts as an energy transformer.

In the test section, the air flow losses most of the pressure energy due to the action of shock waves, but its heat energy remains entirely. After the test section, the testing function of the air flow is complete, and the air, treated as a kind of waste gas, is exhausted into the supersonic diffuser.

In a word, the character of energy change in the conventional hypersonic wind tunnel is that the heat energy in the operation of the tunnel is needed, but isn't consumed; it is kept entirely in the waste gas of the tunnel. The above analysis is based on the ideal flow theory, so the heat loss along its flow course isn't considered; in the actual operation of the tunnel, there exists the loss which can be approximately evaluated by the boundary layer theory.

3.2. Methods to deal with remainder energy in existing conventional hypersonic wind tunnels

The above character of energy change in the conventional hypersonic wind tunnel is the common character of all the existing tunnels, but the existing tunnels with different aerodynamic layouts also have their own characters, mainly focusing on the methods on how to deal with the remainder energy.

Among the existing aerodynamic layouts, the remainder energy is not reclaimed in the intermittent ones, where the remainder energy is exhausted into the atmosphere in the injector one; the energy is consumed by the cooler in the vacuum one, which also needs other energy to keep operation.

In the continuous aerodynamic layout, the waste air is reclaimed, but the remainder energy is not reclaimed and just like that in the vacuum one, consumed by a cooler.

4. Energy-saving and environment-protecting aerodynamic layouts for large-scale conventional hypersonic wind tunnels

4.1. Reclaim methods of remainder energy to be used in conventional hypersonic wind tunnels

Up to now, no reclaim of remainder energy has been considered in the design of the existing conventional hypersonic wind tunnel, so there is no tunnel design experience available on it. To solve the issue, it is necessary to resort the reclaim methods used for industrial remainder heat energy.

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There are now three kinds of methods used in industry to reclaim the remainder heat energy: first, reclaiming by energy storage materials, second, doing by transforming heat energy into other kinds of energy, third, doing by heat exchange, which differ in their own characters, and have different application ranges. For the first case, it is easy in realization, convenient for movement, but suitable only for small amount of remainder heat. The second case is suitable for large amount of remainder heat produced continuously, but the transforming facilities are usually complex. The third case is simple in principles and easy in realization, where the remainder heat is transferred by exchangers to another medium to be heated.

The remainder heat energy in the large-scale conventional hypersonic wind tunnel has such features as large amount, short duration, non-continuous production, and so on. Based on the analysis of the different reclaim methods, it is known that the suitable method for the remainder heat energy in the large-scale conventional hypersonic wind tunnel is the reclaim method by heat exchange, namely, the remainder heat energy is transferred to the coming flow of the tunnel by heat exchangers.

4.2. New aerodynamic layout for large-scale conventional hypersonic wind tunnels

Now, the aerodynamic layouts of the existing conventional hypersonic wind tunnel can be designed to ensure that the wind tunnels all have good-quality flow fields. In the design of the aerodynamic layouts for the large–scale conventional hypersonic wind tunnel, it is not only required that the wind tunnel has good-quality flow field in the simulation range, but also required that the remainder heat energy is saved in the operation of the wind tunnel. To satisfy the requirements, a possible aerodynamic layout for the large-scale tunnel can be designed by combining one of the aerodynamic layouts of the existing tunnels with the reclaim technology of remainder heat energy. There exist two questions in the combination: one is which aerodynamic layout can be selected, another is how to combine the reclaim technology of remainder heat into the aerodynamic layout.

From the analysis on the features of the aerodynamic layouts of the existing conventional hypersonic wind tunnels described above, it is known that in the intermittent wind tunnel with the injector& vacuum type aerodynamic layout, the flow fields have large simulation ranges of Mach number and Reynolds number and have good quality in the simulation ranges; meanwhile, the aerodynamic layout can be easily combined with the reclaim technology. A new aerodynamic layout suitable for the large-scale conventional hypersonic wind tunnel is obtained by combining the intermittent aerodynamic layout of injector& vacuum type with the reclaim technology by exchanger, as shown in Figure7.

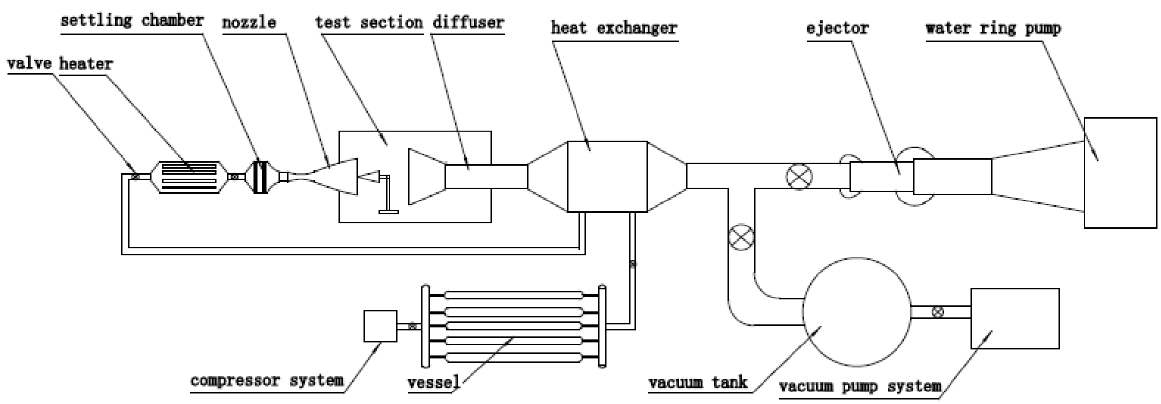

Fig 7. New aerodynamic layout for large-scale conventional hypersonic wind tunnel

4.3. Characters of new aerodynamic layout for large scale conventional hypersonic wind tunnels

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The new aerodynamic layout for large-scale conventional hypersonic wind tunnels is characterized by the changes in structure and operation. The changes in structure mainly includes the following: first, before the injector and vacuum branches and after the supersonic section, a heat exchanger is increased; second, the coming flow from the air source first passes the heat exchanger then enters the heater system; third, in the injector branch, the silencer is displaced by a water ring pump; fourth, the cooler in the vacuum branch is removed.

The operation of the new aerodynamic layout is as follows: the air flow from the air source passes the heat exchanger where it is heated at first, then it enters the heater system where it is heated to the needed temperature; after passing the settling chamber, the nozzle, it forms the flow field with a certain Mach number in the test section; after testing, the air flow enters first the supersonic diffuser for speed reduction and pressure increase, then enters the heat exchanger where the coming flow is heated by the remainder heat energy; at last, the air flow enters the injector branch or the vacuum branch where it is exhausted into the atmosphere.

The critical technologies to realize the new aerodynamic layout are the design methods for the heat exchanger and heater system. The heat exchanger must be highly effective, because the energy-saving effect of the new aerodynamic layout is directly related to the efficiency of the heat exchanger. But the heat exchanger is difficult to design by the common design method for the exchanger due to its design conditions where the heating air flow is the high-temperature low-pressure flow, and the air flow to be heated is the flow of low-temperature high-pressure flow; at the same time, the heat should be exchanged sufficiently and the temperature at the exit of the heat exchanger should be below 370K. In order to design the heat exchanger needed in the new aerodynamic layout, the following problems should be solved: first, what is the heat exchanging mechanism to be used; second, how to calculate the feature coefficients of the exchanger; third, what is structure type of the exchanger; and so on.

During the operation of the new aerodynamic layout, the feature coefficients of the heater are correlated with those of the heat exchanger. In order to design the heater suitable for the new aerodynamic layout, the following problems should be solved: first, what is the operation type of the new aerodynamic layout; second, how to calculate the feature coefficients of the heater; third, what is structure type of the heater; and so on.

5. Calculation of Energy-saving effect of aerodynamic layout for large-scale conventional hypersonic wind tunnels

To evaluate the energy-saving effect of the new aerodynamic layout, a simple calculation about the remainder heat to be utilized in the new layout is conducted. The calculation conditions are: Mach number is 5; nozzle exit diameter is 2400mm; the total pressure is 3.0MPa; the coming air flow is heated from 298K to 1300K; the run time is 120 seconds. According to the flux formula, the flux of the air flow is,

$$G \approx 602.26 \text{ Kg/s}$$

The increased heat in the air flow per second is,

$$Q \approx 641784.52 \text{ KJ/s}$$

The total heat increased in the air flow during run time is,

$$W = 120 \times Q \approx 7.7\text{x}10^{7} \text{ KJ}$$

As described above, when the heat loss along the course of air flow is considered, the remainder heat may be about 80% of the total increased heat of air flow; when an heat exchanger with high efficiency is used, the heat exchanging rate should be more than 80%, so the saved energy during each run of the new aerodynamic layout can be calculated as the following,

$$SN = 0.8 \times 0.8 \times W \approx 4.93\text{x}10^{7} \text{ KJ}$$

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This is the net heat transferred into the air flow by the heat exchanger. If the heat of air flow is obtained through the heater system, on consideration of the efficiencies of heating and exchanging of the heater system, the actually needed heat is much more than the net heat.

If the remainder heat of wind tunnel heater system is considered , then the schematic layout for further heat reclaim of heater system after the operation of the large-scale conventional hypersonic wind tunnel based on the above energy-saving layout is shown in Figure 8,

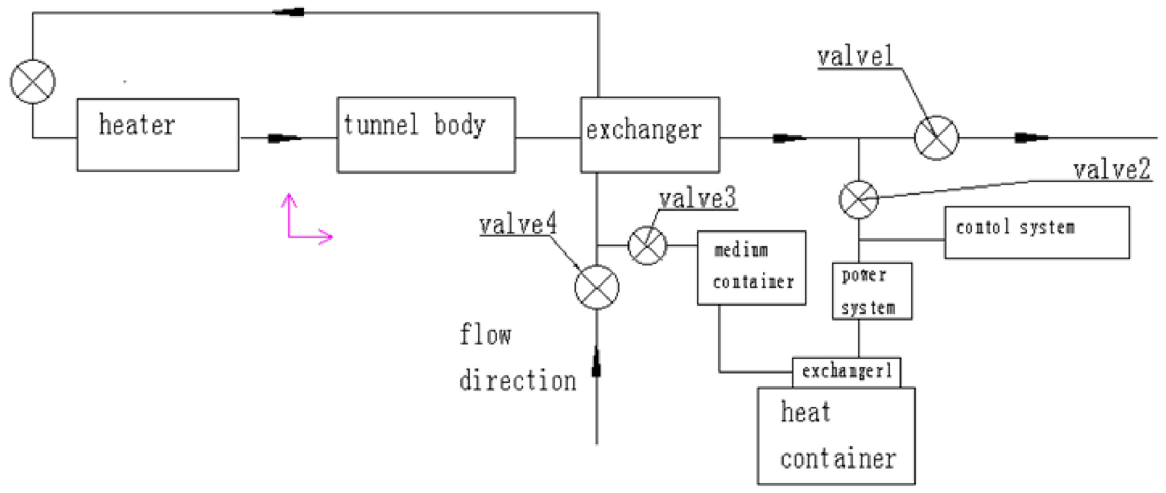

Fig 8. Schematic layout for heat reclaim of heater system based on energy-saving layout

6. Conclusion

Based on the summary of the aerodynamic layouts of the existing conventional hypersonic wind tunnels, a new aerodynamic layout for the large-scale conventional hypersonic wind tunnel is put forward by considering the characters of the energy change in the conventional hypersonic wind tunnel. It is shown by a simple evaluation results that the new aerodynamic layout is an energy-saving and environment-protecting layout. Meanwhile, the critical technologies for the realization of the new layout are also discussed, and a schematic layout for further reclaim of the heater system after the operation of the large-scale conventional hypersonic wind tunnel is presented.

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