

CHAPTER 19

Wind turbine cooling technologies

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With the increase of the unit capacity of wind turbines, the heat produced by different components rise significantly. Effective cooling methods should be adopted in developing larger power wind turbine. In this chapter, the operating principle and main structure of wind turbines are firstly described, following with the analysis of heat production mechanisms for different components. On this basis, current cooling methods in wind turbines are presented. Also, optimal design of a liquid cooling system for 1 MW range wind turbine is conducted. Finally, some novel cooling systems are introduced and discussed.

1 Operating principle and structure of wind turbines

In brief, the operating principle of a wind turbine is that rotation of impellers driven by wind power converts the kinetic energy of wind into mechanical energy of the impeller shaft, which drives the generator. There are mainly two types of wind turbine operating modes. One is the independent power-supply system, which is usually used in the remote areas, where electric network is not available. The terminal electrical equipments are powered by alternating current, which is converted by a DC-AC converter from the electricity in a storage battery charged by small scale wind turbines. Generally, the unit capacity is from 100 W to 10 kW. Or a hybrid power-supply system comprising a middle scale wind turbine and a diesel generator or solar cells with capacity, range from 10 to 200 kW, is adequate to meet the need of a small community. In another wind turbine operating mode, the wind turbines are used as a power resource of an ordinary power network, paralleling in the electricity grid system. It is the most economic way to utilize wind power in a large scale. This mode can synchronize and close with a unit independently and also can be made of multiple, or even thousands of wind turbines, called wind farm [1-3].



As shown in Fig. 1, a wind turbine working in a parallel operation is mainly comprised of an impeller, a nacelle, a pylon, a foundation and an electric transformer. Among these components, the impeller is wind collecting device, including blades and hub. It can convert wind power at a certain height to mechanical energy, representing as shaft rotation at a low speed but with high torque. The nacelle, comprised of a gearbox, a generator and control systems, is the core component of the wind turbine where the mechanical movement is accelerated, then converted to electric energy with modulated frequency to meet the demands of parallel operation. The pylon and foundation are mostly used to support the nacelle and impeller to a certain height and ensure the safe operation. The function of the electric transformer is to perform the voltage regulation to the output electricity so as to transfer power efficiently.

To sum up, the operating procedure of a wind turbine is as follows: the impeller rotating under the wind force action drives the main shaft in the nacelle to rotate simultaneously. This movement is then accelerated in the gearbox, and supplies the high-speed revolution for the generator rotor by connecting with high-speed shaft. The rotor cuts the magnetic lines of force, and thus produces electric energy. With the increasing unit capacity of wind turbines, the length of impeller blades and the height of pylon are gradually increased for the purpose of capturing more wind energy.

2 Heat dissipating components and analysis

It is well known from the operation principle mentioned in Section 1, the nacelle is the core component for a wind generating set and also the concentrated area of heat production in the operating process. The configuration of the nacelle is shown in Fig. 2, and the mechanisms of heat production for different components are explained as follows.

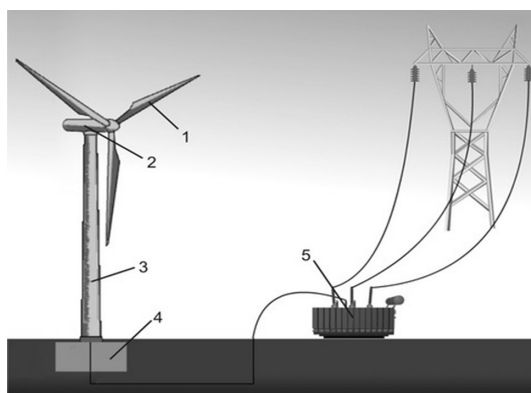


Figure 1: Sketch of a wind turbine generator connecting to power system: 1, impeller; 2, nacelle; 3, pylon; 4, foundation; 5, transformer.

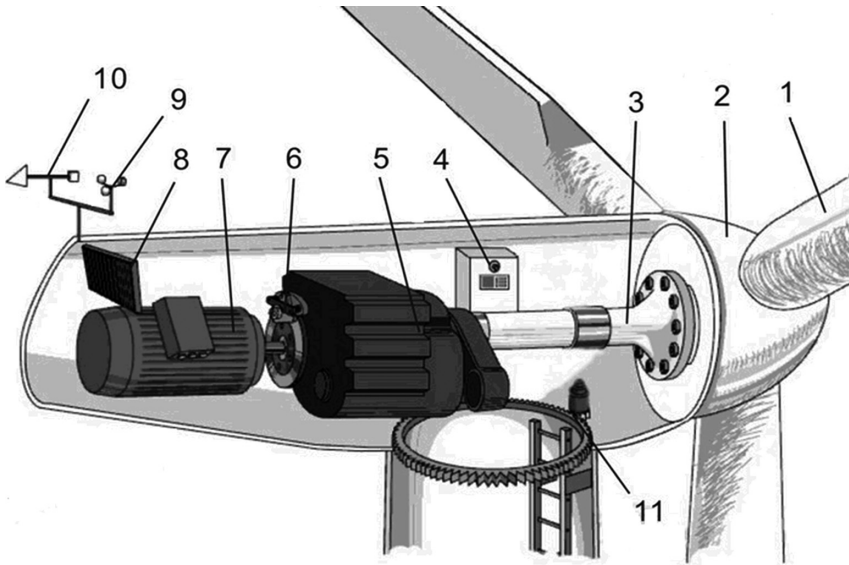


Figure 2: Sketch of a wind generating set [4]: 1, impeller blades; 2, hub; 3, main shaft; 4, controller; 5, gearbox; 6, mechanical brake; 7, generator; 8, cooling system; 9, anemoscope; 10, wind vane; 11, yawing motor and yawing bearing.

2.1 Gearbox

The gearbox is the bridge connecting the impeller and the generator. Since the rotational speed of an impeller is between 20 and 30 rpm, and the rated speed of a generating rotor is from 1500 to 3000 rpm or even higher, therefore a gearbox has to be installed between the impeller and the generator to accelerate the low-speed shaft. The running gearbox causes some power loss, most of which transfers into heat and is absorbed by the lubricating oil and, thus, causes temperature rising in the gearbox. If this temperature becomes too high, it will deteriorate the performance of lubricating oil, causing lower viscosity and shorter drain period. Moreover, it also increases the possibility of damage to the lubricating film under load pressure, which leads to impairment of the gear meshing or the bearing surface and, eventually, the equipment accident. Therefore, restriction of temperature rise in the gearbox is a key prerequisite for its endurable and reliable operation [5]. On the other hand, in winter, when the ambient temperature is below 0°C , heating measure for the lubricating oil in gearbox should also be taken into consideration in order to avoid lubricating oil from failing to splash onto the bearing surface due to high viscosity in low temperature, and, therefore, prevent impairment of the bearing from short of lubrication. Normally, every large-scale wind turbine gearbox contains a compelling cooling system and a heater for lubricating oil. However, in some regions where the temperature seldom drops below 0°C , such as the coastal areas in Guangdong Province, China, heaters can be an exemption [6].

2.2 Generator

The generator rotor is connected to the high-speed shaft of the gearbox. It drives the generator to rotate at a high speed and to cut the magnetic lines of force, by which electric energy is obtained. During the operation of a wind turbine, the generator will produce a huge amount of heat mainly in its windings and various internal wastes of iron core, primarily comprised of iron loss, copper loss, excitation loss and mechanical loss [7]. Besides, the temperature rise of the generator also has a correlation with power, operational condition, and duration of runs [8]. Moreover, there is a tendency of the unit-capacity enlargement of wind turbine which can be implemented by magnifying winding factor or magnetic field intensity. Since adding electromagnetic load is unsatisfactory with the restriction of magnetic saturation, at present, a popular method for enlarging the unit capacity is to increase inductance coil load. However, by applying this method, copper loss of bar will rise, which results in high coil temperature, acceleration of insulation aging and, eventually, damage of the machine. Because of this, a proper cooling method should be applied to control the internal temperature of various components of the generator within a permissible range. Hence, it can be concluded that the enlargement of the unit capacity of wind turbine mainly depends on the improvement of the cooling technology [9, 10].

2.3 Control system

As the wind speed and direction are changing all the time in the operation of wind turbine, auxiliary apparatus should be installed to adjust the operating status promptly to ensure the secure and stable operation of the wind turbine. The common system auxiliary apparatuses include: anemoscope, wind vane, yawing system, mechanical brake and thermometer. The anemoscope and the wind vane are used to detect immediate wind status; and the thermal sensor is responsible for monitoring the temperature changes in the generator and gearbox. When the operating status changes, the anemoscope, the wind vane and the thermal sensor will feed back the detected signal to the control system in the nacelle, then the input signal is diagnosed and processed by the control system and finally output to the yawing system and the mechanical brake, which changes the operating status of the wind turbine. Meanwhile, the control system has functions of displaying and recording parameters such as instantaneous mean wind speed, mean wind direction and mean power and other operating parameters. In addition, frequency converter is equipped in the control system, which aims at converting the unstable frequency of wind turbine signal to suffice to the demands of parallel operation. Therefore, the control system is also called control converter. In the operation, as a core component for the failure-free operation of wind turbine, the control system will produce a large amount of heat, which needs to be taken away timely.

3 Current wind turbine cooling systems

As has been mentioned above, in the operation of wind turbine, the gearbox, generator and control system will produce a large amount of heat [11]. In order to ensure the secure and stable operation of wind turbine, effective cooling measure has to be implemented to these components. Since the early wind turbines had lower power capacity and correspondingly lower heat production, the natural air cooling method was sufficient to meet the cooling requirement. As the power capacity increases, merely natural air cooling can no longer meet the requirement. The current wind turbines adopt forced air cooling and liquid cooling prevalently, among which, the wind generating set with power below 750 kW usually takes forced air cooling as a main cooling method. As to large- and medium-scale wind generating set with power beyond 750 kW, a liquid recirculation cooling method can be implemented to satisfy the cooling requirement [11].

3.1 Forced air cooling system

The forced air cooling system comes up where a natural air cooling system cannot meet the cooling demands. When the air temperature in the wind turbine exceeds a certain prescribed value, to achieve the cooling objective, the control system will open the flap valve connecting internal and external environment of the nacelle and, meanwhile, fans installed in the wind turbine are switched on, which produce forced air blast to the components inside the nacelle. As the performance of air cooling ventilation system has a decisive influence on the cooling effect and operating performance of the wind turbine, the ventilation system should be well designed [9]. Thus, the design of the ventilation system is vital to an air cooling system project.

In the implementation of a forced air cooling system, different combinations are chosen according to the amount of system heat production and heat dissipation of various components. For a wind turbine with a power below 300 kW, since the heat dissipation of the generator and control the converter is relatively low, their heat is removed mainly by the cooling fans installed on the high-speed shaft, and the gearbox is cooled using a method of splash lubrication due to the rotation of the gear, where the heat of formation (or producing heat) is delivered through the gearbox and additional fins to the nacelle, and finally taken away by the fans. The cooling performance is mainly subject to the ventilating condition in nacelle [5]. By comparison, a wind turbine with power capacity beyond 300 kW possesses a comparatively larger heat production and, therefore, it is not sufficient for the gearbox to control the temperature rise only by the cooling fan installed on the high-speed shaft and the radiated rib on the box. The method of lubricating oil circulation can realize effective cooling. The basic operating procedure is described as follows: the gearbox is configured with an oil circulation supply system, driven by a pump and an external heat exchanger. The oil temperature can be adjusted under the permissible maximum value by regulating the oil delivery rate and the wind speed flowing through the heat exchanger according to the temperature rise

status of the lubricating oil. This circulating lubrication cooling method is mature and secure in performance, while, on the other hand, it introduces a set of attachments which costs about 10% of the gearbox's manufacturing cost [5]. Considering the cooling for the increasing heat production in the generator and the converter, it can be implemented by enlarging the internal ventilation space and internal air passage of coil. Usually, the generator has both internal and external fans. And the radiating rib with an internal air passage is welded on the outer edge of the stator frame. Thereby, the internal circulating cooling air follows a circuit flowing through the terminal stator winding, iron core and the internal air passage of the radiating rib, while the external cooling air flows directly through the surface of the radiating ribs, as shown in Fig. 3 [12]. Theoretically, the more input air and the higher speed of the fan, the better the cooling effect. However, this will lead to increase flow resistance and power consumption, all of which result in a lower generator efficiency. Therefore the working condition of the generator fan should be designed rationally [13].

Comparing with other cooling method, the forced air cooling system has several advantages, such as simple structure, easy management and maintenance, and low initial and running cost. However, since the cooling air is from external environment, the cooling performance might become low because of the environment

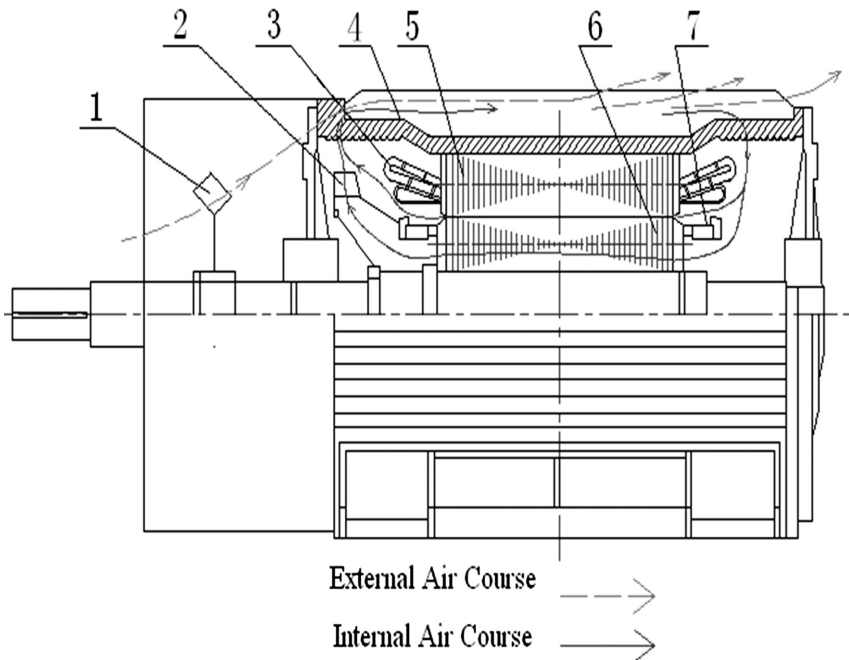


Figure 3: Forced air cooling method for generator: 1, external fan; 2, internal fan; 3, stator winding; 4, stator frame; 5, stator iron core; 6, rotor iron core; 7, rotor winding.

changes. Furthermore, during the ventilation of the nacelle, the severe corrosion on the set possibly caused by blown sand and rain goes against the long-term secure operation of the set. As the power capacity of the wind generating set keeps increasing, merely adopting forced air cooling method could not meet the cooling demands. Hence, liquid cooling systems are emerging.

3.2 Liquid cooling system

From the thermodynamics knowledge, the thermal equilibrium equation of a wind turbine cooling system can be described as $Q = q_m C_p (t_1 - t_2)$, where Q is the total system heat, q_m is the mass flux of the cooling medium, C_p is the mean specific heat at constant pressure of the cooling medium between temperature t_1 and t_2 . t_1 and t_2 are the inlet and outlet temperature of the cooling medium. As the liquid medium's concentration and specific heat capacity are much greater than that of the gaseous medium, the cooling system adopting liquid medium can obtain much larger cooling capability as well as a more compact system structure which can solve the problem of low cooling output and the enormous size of the air cooling system. The structure of the cooling system is shown in Fig. 4.

During the operation of a wind turbine, the cooling medium firstly flows through the oil cooler, exchanging heat with lubrication oil and taking away the heat produced by the gearbox. Then it flows into the heat exchanger fixed around the stator

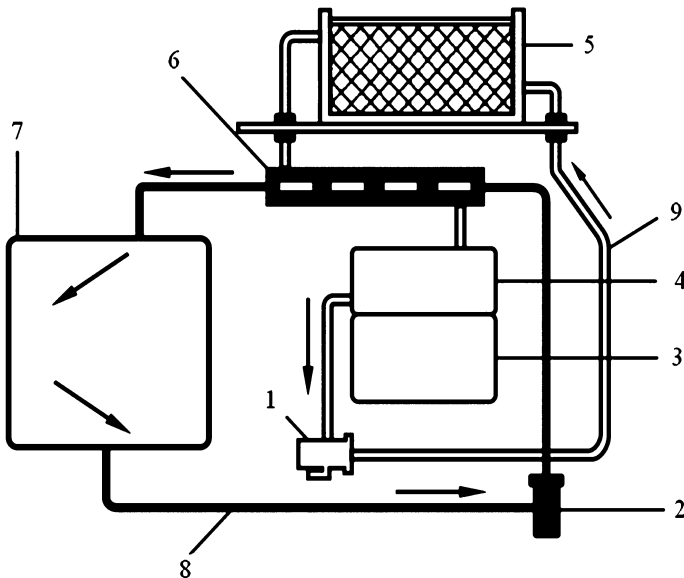


Figure 4: Cooling system adopting liquid cooling method [9]: 1, water pump; 2, oil pump, 3, generator; 4, generator heat exchanger; 5, external radiator; 6, oil cooler; 7, gearbox; 8, lubricating oil pipeline; 9, cooling medium pipeline.

winding, absorbing the heat produced by the generator. Finally, it will be pumped out and get cooled by an external radiator, by which the flow is prepared for the next cycle of heat exchange. In normal working condition, the cooling water pump always stays in working mode to deliver the internal heat to the external radiator through cooling medium. And the lubricating oil pump can be controlled by the temperature sensor in the gearbox. When the oil temperature exceeds the rated value, the pump switches on, delivering the oil to the oil cooler outside the gearbox; while the oil temperature falls below the rated value, the circuit is cut off to stop the cooling system. Besides, as the control converter in each wind generating set varies to each other, there will be difference in the amount of heat produced among these converters. When the heat production is relatively low, the forced air cooling generated by the fan fixed in the nacelle is sufficient for the control converter and other heat producing components; while if the heat production is comparatively large, a radiator outside the control converter can be installed to control its temperature rise through cooling medium taking away the heat in the same way of gearbox and generator.

With respect to the MW wind turbine with a larger power capacity, the gearbox, generator and control converter all produce comparatively large amount of heat. As shown in Fig. 5, cooling these components mentioned above usually needs two independent sets of cooling system – one shared by the generator and control converter and the other for the gearbox [14]. In an oil cooling system, the lubricating oil is pumped up to lubricate the gearbox; the heated oil is then to be delivered to the oil cooler on top of the central nacelle to be cooled by forced air. The cooled lubricating oil is then delivered back to the gearbox for use of the next cycle. A liquid cooling system is a closed-loop system containing an ethylene glycol aqueous solution-air heat exchanger, a water pump, valves, and control devices for temperature, pressure and flux. The cooling medium in the closed-loop system flows through the generator and the control converter to take away their produced heat.

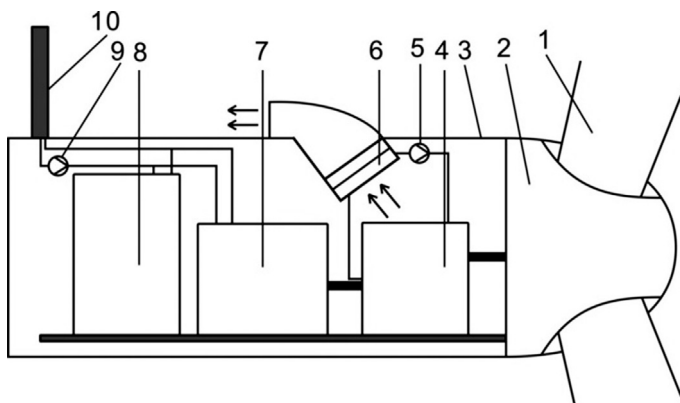


Figure 5: A cooling system for one MW wind turbine [14]: 1, blade; 2, hub; 3, nacelle; 4, gearbox; 5 and 9, hydraulic pump; 6, oil cooler; 7, generator; 8, converter; 10, heat exchanger.

Then it gets cooled in the external radiator on top of the rear of the nacelle, and finally runs back to the generator and the control converter to begin the next cooling cycle.

At present, the cooling mediums commonly used in the liquid cooling system are water and ethylene glycol aqueous solution. Comparing with water, ethylene glycol aqueous solution has better anti-freeze property. Table 1 shows freezing points of ethylene glycol aqueous solution in different densities. By adding a certain amount of stabilizers and preservatives, the minimum working temperature can extend to -50°C , but keeps its heat transfer performance equivalent to that of water [19].

Besides, in order to enhance the heat-exchange performance, the external heat exchanger adopts an effective and compact plate-fin structure, which is usually made of the light metal, aluminum. The heat exchanger exposed to the external environment is prone to be corroded, which will affect the durable, reliable operation of the heat exchanger. Therefore, necessary anti-corrosion treatments need to be implemented, like coating the aluminum flakes with anti-corrosive allyl resin coverings and employing hydrophilic membranes on its outer surface. Having been treated with this method, the acid rainproof of the aluminum fins and the anti-salt corrosion property can be 5–6 times as large as those of the ordinary ones. In the design of the heat exchanger, due to relatively large difference of the cooling system operating loads in winter and summer, the summer operating mode is adopted as the design condition, while the heat transfer efficiency can be controlled through a bypassing method in winter.

Comparing with the wind turbine adopting the air cooling method, the one adopting liquid cooling system has a more compact structure. Although it increases the cost of heat exchanger, cooling medium and corresponding laying of connecting pipelines, it extremely enhances the cooling performance for the wind generating

Table 1: Freezing points of ethylene glycol aqueous solution in different densities.

Density (%)	Freezing point ($^{\circ}\text{C}$)
0	0
5	-2.0
10	-4.3
20	-9
30	-17
40	-26
50	-38
60	-50.1
70	-48.5
80	-41.8
85	-36
90	-26.8
100	-13

set, and thus facilitates the generating efficiency. Meanwhile, the design of the sealed nacelle prevents the invasion of wind, blown sand and rain, creating a good working surrounding for the wind turbine, which greatly extends the duration of the devices.

4 Design and optimization of a cooling system

As has been mentioned above, the increasing power capacity of wind turbines calls for a matching cooling system. With the widespread use of MW wind turbines, the liquid cooling system has been prevalently used in current wind turbines. Accordingly, the design and optimization of a liquid cooling system is briefly introduced in this section. Since currently very few researches are conducted on the heat dissipating regularity in wind turbine operation and experimental data are scarce, the following research is based on a steady working condition, where the heat production of the generating set is under a steady-state condition. According to the ambient conditions and technical requirements provided by wind turbine companies, the liquid cooling system is designed and analyzed under the maximum heat load. On this basis, the commercial software, MATLAB, is used for the purpose of optimal design, and the interaction and mechanism of action are investigated among parameters, such as wind speed, fin combinations, etc. These researches are somehow valuable to be referred to for the design and optimization of the MW wind turbine cooling system.

4.1 Design of the liquid cooling system

The cooling system of one certain MW wind turbine is shown in Fig. 5. This section proposes the design of the liquid cooling system for the generator and the control converter, which is shown as follows [14]. And as the designs of oil cooling system and liquid cooling system are basically the same, contents on those will be excluded due to restriction of the article length.

4.1.1 Given conditions

This MW wind turbine is located in the coastal area with a temperature ranging from -35 to 40°C . The start-up wind speed is 4 m/s , while the shutdown wind speed is 25 m/s . The relationship between the generated output P and wind speed $V_{c,in}$ is shown in Fig. 6. Other initial parameters are shown in Table 2. The objective is to design a liquid cooling system to meet the cooling demands of the wind turbine and to control its structural sizes to be most favorable for the durable operation of the wind turbine based on the giving ambient conditions and technical requirements from the wind turbine companies. Focusing on this objective, this section introduces how to select key components and explain the method of optimal computation to obtain the size of the ethylene glycol aqueous solution-air-typed heat exchanger.

4.1.2 Selection of the cooling medium

To meet the technical requirement of -35°C for the minimum ambient temperature in winter, the ethylene glycol aqueous solution with a concentration of 50% and a freezing point of -38°C is picked according to Cao [15] and Tan [16].



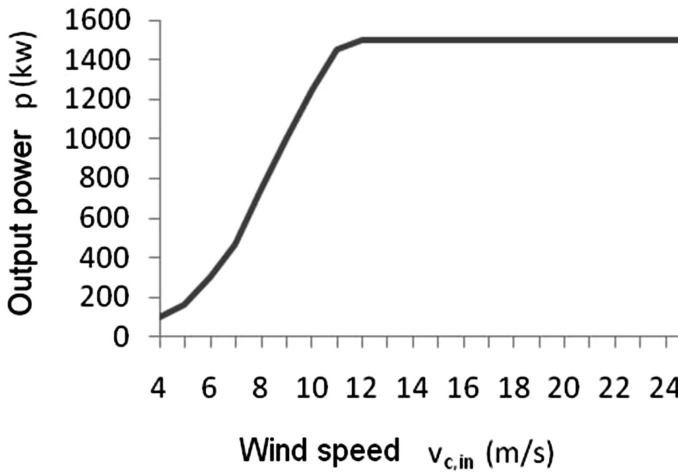


Figure 6: Relationship between the generated output of the wind turbine and the wind speed [14].

Table 2: Given parameters.

Items	Generator	Control converter	External radiator
Efficiency, η	97%	—	—
Heat dissipation (kW)	3% of the output	19	—
Maximum inlet water temperature ($^{\circ}\text{C}$)	50	45	—
Flux (l/min)	50	60	—
Pressure loss (MPa)	0.08	0.1	≤ 0.01 liquid side
External dimensions (m \times m \times m)	—	—	$1.900 \times 0.820 \times 0.200$

4.1.3 Selection and design of the radiator

Normally, the operating performance of a cooling system mainly depends on the selection and the design of the heat exchanger. The heat exchanger in a practical operation should be, more or less, vibration-proof, because the vibration in the nacelle is driven by wind. In addition, if the wind turbine is located in a coastal area with comparatively high humidity, the heat exchanger should be corrosion-proof as well. Considering all the requirements mentioned above, the final choice for the radiator is an aluminum plate-fin heat exchanger with not only high heat transfer efficiency, but also a compact, light and firm structure [17, 18]. As shown in Fig. 7, where Channel A is air-flow passage, and B is the channel for ethylene glycol aqueous solution. The distribution of the channel is ABABABAB.... The detailed design of this cross-current plate-fin heat exchanger can be referred to Wang [17] and only necessary introduction is covered in this section due to space limitation.

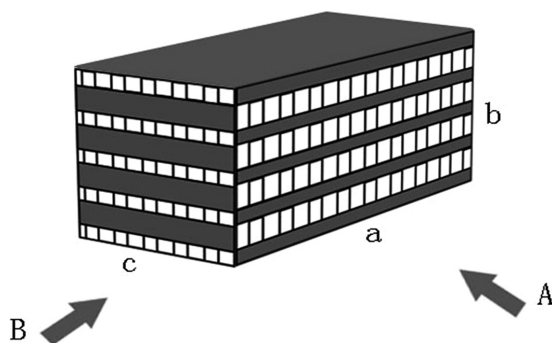


Figure 7: Core unit of a cross-current plate-fin heat exchanger [17]: (A) air-flow passage; (B) ethylene glycol aqueous solution channel; (a) the width of the core unit; (b) height of the core unit; (c) thickness of the core unit.

4.1.3.1 Selection of the fin unit and related dimension calculation

1. Calculation of the heat transfer area of air side and liquid side.
Assuming that the density, thermal coefficient, constant-pressure specific heat capacity and kinetic viscosity of air and ethylene glycol aqueous solution stay constant in the heat transfer, their values are selected according to the inlet and outlet mean temperature.
2. Calculation of heat transfer temperature difference and heat transfer coefficient.
3. Fin efficiency and surface efficiency of the air side and liquid side.
4. Total heat transfer coefficient of the air side and liquid side.
5. Checking and calculating heat exchanger thickness.

After obtaining the heat transfer coefficient and logarithmic mean temperature difference of both air side and liquid side, the real transfer area and heat exchanger thickness can be calculated. If the actual calculated thickness c_{real} of heat exchanger does not equal the given c , the value of c should be reassumed and calculated following steps (1)–(5) of the flow path until the calculated c_{real} equals the default c .

4.1.3.2 Calculation to other parameters of the heat exchanger

1. Pressure loss on the liquid side.
In order to meet the technological requirement and the pump selection requirement, the resistance of the heat exchanger should be checked in the design process. When the fluid is in a pump circulation in the plate-fin heat exchanger, the resistance calculation can be divided into three parts, i.e. inlet tube, outlet tube and central part of the heat exchanger [17].
2. Calculation of heat exchanger efficiency and weight.

4.1.3.3 Selection of the head plate for the plate-fin heat exchanger

According to Liu *et al.* [19] and Zhou *et al.* [20], staggered perforated plate header is selected in order to obtain well-proportioned flux distribution and well-controlled fluid friction loss.

4.1.3.4 Anti-corrosion measures

The heat exchanger exposed to the external environment is prone to be corroded, which will affect the durable, reliable operation of the heat exchanger. Therefore, necessary anti-corrosion treatments need to be implemented, like coating the aluminum flakes with anti-corrosive allyl resin coverings and employing hydrophilic membranes on its outer surface. Having been treated with this method, the acid rainproof of the aluminum fins and the anti-salt corrosion property can be 5–6 times as large as those of the ordinary ones. In the design of the heat exchanger, due to relatively large difference of the cooling system operating loads in winter and summer, the summer operating mode is adopted as the design condition, while the heat transfer efficiency can be controlled through a bypassing method in winter.

4.1.4 Flow resistance calculation of the liquid cooling system and pump selection

The liquid cooling pipeline system is comprised of a steel tube part and a pressure hose part. In view of the various factors, the following pipe diameters should be selected: steel tube and pressure hose diameter of the main trunk $D_1 = 48$ mm, branch steel tube and pressure hose's diameter $D_2 = 42$ mm. The on-way resistance and local resistance can be calculated based on the selected tube diameter, with which the circulating pump can be selected.

4.2 Optimization of the liquid cooling system

Based on the design method mentioned above, by utilizing MATLAB software, the optimization of the liquid cooling system is performed. Since the external radiator is the core component of the liquid cooling system, its structural dimension has an important impact on the cooling effect of the wind turbine and the weight of the nacelle. The subject of optimization in this section is the external radiator shown in Fig. 5. The constraint conditions are: the external radiator is fixed in the frame on top of the rear of the nacelle, with a limitation of frame size of $1.900\text{ m} \times 0.820\text{ m} \times 0.200\text{ m}$; and the actual maximum size of the core unit of the external radiator is $1.800\text{ m} \times 0.800\text{ m} \times 0.200\text{ m}$ excluding the size of stream sheet and head. Under these conditions, the optimization procedure is shown as follows.

4.2.1 Derivation of the thickness of the heat exchanger core unit

The functional relation of the thickness of the heat exchanger can be derived from the heat transfer equation and the heat transfer coefficient equation and so forth as follows:

Total heat transfer:

$$Q = k_h \Delta t_m F_h \quad (1)$$

where Q is the heat transfer quantity of the heat exchanger, k_h is the total heat transfer coefficient on the liquid side, Δt_m is the heat transfer mean temperature difference, F_h is the total heat transfer area on the liquid side, given as



$$F_h = f_1(c, cc, ch) \quad (2)$$

where c is the thickness of the core unit of the heat exchanger, cc is the dimension of the fin unit on the airside, and ch is the fin unit dimension on the liquid side.

From eqns (1) and (2), the core unit thickness is obtained as

$$c = f_2(Q, k_h, \Delta t_m, cc, ch) \quad (3)$$

From the known condition:

$$Q = f_3(v_{c,in}) \quad (4)$$

Total heat transfer coefficient:

$$k_h = f_4(\alpha_c, \alpha_h, \eta_{0,c} \cdot \eta_{0,h}, F_c, F_h) \quad (5)$$

Heat transfer coefficient on the airside:

$$\alpha_c = f_5(v_{c,in}, cc) \quad (6)$$

Heat transfer coefficient on the liquid side:

$$\alpha_h = f_6(v_h, ch) \quad (7)$$

Flow velocity of the fluid:

$$v_h = f_7(c, cc, ch) \quad (8)$$

Fin efficiency on the air side:

$$\eta_{0,c} = f_8(cc, \alpha_c) \quad (9)$$

Fin efficiency on the liquid side:

$$\eta_{0,h} = f_9(ch, \alpha_h) \quad (10)$$

Total heat transfer area on the airside:

$$F_c = f_{10}(c, cc, ch) \quad (11)$$

From eqns (2), (5) and (11), the total heat transfer coefficient based on the total heat transfer area on liquid side can be expressed as

$$k_h = f_{11}(c, cc, ch, v_{c,in}) \quad (12)$$

Heat transfer mean temperature difference,

$$\Delta t_m = f_{12}(t_{c,in}, t_{c,out}, t_{h,in}, t_{h,out}) \quad (13)$$

where $t_{c,in}$ and $t_{c,out}$ represent the inlet and outlet temperature of the air, $t_{h,in}$ and $t_{h,out}$ are inlet and outlet temperatures of the ethylene glycol aqueous solution respectively, in which $t_{c,in}$ and $t_{h,out}$ are known quantities.



In addition that

$$t_{c,out} = f_{13}(cc, ch, v_{c,in}, Q) \quad (14)$$

$$t_{h,in} = f_{14}(Q) \quad (15)$$

From eqns (13) and (15):

$$\Delta t_m = f_{15}(c, cc, ch, v_{c,in}) \quad (16)$$

After substituting eqns (4), (12) and (16) into eqn (3), the functional relation of the heat exchanger's thickness can be simplified to:

$$c = f_{16}(cc, ch, v_{c,in}) \quad (17)$$

On the basis of the deduced relational expression of the heat exchanger's thickness, the thickness dimension is optimized with a method as follows.

Assume that when the wind turbine is running the wind speeds $v_{c,in}$ are under n different circumstances and, thus, there will be n pairs of generated output values and heat dissipation values corresponding to them. After choosing a dimension pair of the fin ('cc' and 'ch' in the equation), n different thicknesses of the heat exchanger core unit ('c') would be obtained, matching n circumstances, respectively, according to the above equations. On this basis, by changing Z types of fin pairs on the air and liquid sides, Z heat exchanger core unit thicknesses meeting design requirements ($c_{max1}, c_{max2}, \dots, c_{maxz}$) can be obtained; therefore Z corresponding resistance on the liquid side and the heat exchanger weight can be obtained. The optimization computing task of the heat exchanger core unit is to find an air-and-liquid-side fin pair solution that not only can meet the cooling demands under various working condition, but also is able to minimize the system power consumption or the total weight of the system.

4.2.2 Optimization procedure of the heat exchanger core unit

1. As the wind turbine usually works under the condition that the wind speed exceeds 8 m/s, thus only the condition with a wind speed ranging from 8 to 25 m/s will be considered. Giving a state point every time by increasing speed of 1 m/s, the wind will be with 18 different velocities. The rated heat dissipating capacity of the radiator corresponding to various wind velocities can be obtained from the generator power graph, shown in Table 3 and Fig. 6.
2. Based on the overall consideration of the maximum rated inlet temperature required for the generator and the control converter as well as the temperature rise of fluid in the pipeline network, the radiator outlet ethylene glycol aqueous solution temperature can be selected as: $t_{h,out} = 43^\circ\text{C}$. Other hypotheses are the same with the statement in Section 4.1.
3. Assuming that the airside fin and the liquid side fin are selected from one of the five types of straight fins and one of the five types of serrated fins, respectively, the collocation types for the air and liquid side fin pairs sums up to 25, with their specific parameters shown in Table 4.



Table 3: Relationship between inlet air velocity and heat dissipation of the heat exchanger [21].

$v_{c,in}$ (m/s)	Q (kW)
8	41.5
9	49
10	56.5
11	62.5
12	64
13	64
14	64
15	64
16	64
17	64
18	64
19	64
20	64
21	64
22	64
23	64
24	64
25	64

Table 4: Parameters of the air and liquid side fin pairs [21].

Parameter	Types of the air side fin pairs					Types of the liquid side fin pairs				
	cc1	cc2	cc3	cc4	cc5	ch1	ch2	ch3	ch4	ch5
Fin height, L_c (mm)	12	9.5	6.5	4.7	3.2	3.2	4.7	6.5	9.5	12
Fin height, δc (mm)	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
Fin interval, mc (mm)	1.4	1.7	1.7	2.0	4.2	4.2	2.0	1.4	1.7	1.4

The optimization procedure is shown in Fig. 8. The computational procedure is as follows. Firstly, choose an air and liquid side fin pair. Secondly, read the wind velocity and rated heat dissipating capacity of the heat exchanger and then calculate the heat exchanger thickness c to satisfy these conditions using an iterative method. Finally, calculate the weight of the heat exchanger core unit, pressure drop on the liquid side and other parameters like heat exchanger efficiency and so forth until all the calculation completes.

4.2.3 Interpretation of the optimization computing result

4.2.3.1 Wind condition numbers corresponding to the calculated heat exchanger thicknesses larger than 0.2 m based on various fin pair collocations

After choosing any air and liquid side fin pair, 18 heat exchanger thicknesses can be obtained corresponding to 18 wind conditions in order to match the cooling



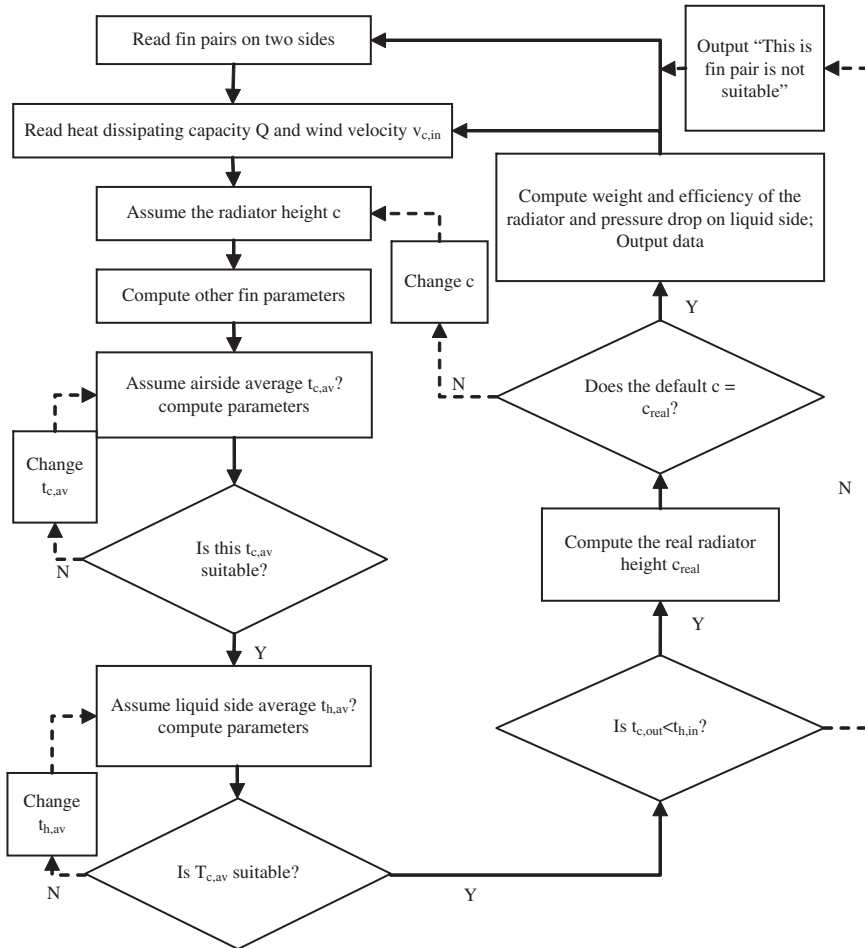


Figure 8: Flow chart of the optimization and computation of the radiator.

demands of the system. The calculated results by MATLAB forms are in Fig. 9. It can be concluded from the figure that, as the fin height on the airside declines, the fin height on the liquid side rises and the wind condition numbers with a heat exchanger thickness exceeding 0.2 m increases correspondingly, thus leading to an unreasonable collocation.

4.2.3.2 Selected heat exchanger thickness corresponding to different fin pairs and the weight of the heat exchanger

When the 18 values of c (heat exchanger thickness) are all less than 0.2 m corresponding to 18 wind conditions, it indicates that this fin pair can meet the system's cooling and dimension requirements simultaneously. Similarly, it can be found that when the fin pair is cc1 and ch1, indicating that the airside fin height reaches its maximum and that of the liquid side is of its minimum, the selected thickness c_{\max} and weight W_{\max} is the smallest, and thus the structure of the heat exchanger

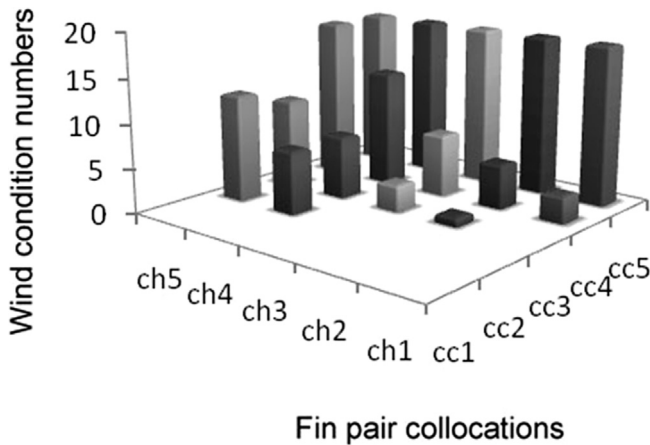


Figure 9: Wind condition numbers corresponding to heat exchanger thickness exceeding 0.2 m based on various fin pair collocations [21].

is the most compact and lightest under this circumstance. Moreover, it can be found in the figure that if the airside fin size is changed and the liquid fin size is kept unchanged, there will be an obvious influence on the selected heat exchanger thickness and weight; while if the liquid side fin is changed instead of the airside one, the change will be comparatively smaller.

It can be found from the above computing results, the heat exchanger adopting fin pair cc1 and ch1 can reach its lightest and most compact structure, which is, thus, in favor of operating at a high altitude for the generating set. Considering that the liquid side pressure drop is far less than that of the cooling medium running through the generator and the control converter, this optimization focuses on the weight of the cooling system. From computing results, the fin pair cc1 and ch1 are adopted as the optimum fin pair. The results show that it would obtain a more effective fin function and comparatively higher fin efficiency by selecting low and thick fin on the liquid side with a large heat transfer coefficient and by selecting the high and thin fin on the small-heat-transfer-coefficient airside.

The relationship, shown in Fig. 10 [21], between the computed values of the parameters and the wind speeds under 18 wind conditions adopting fin pair cc1 and ch1 are computed by the commercial software, MATLAB. It can be concluded from the modeling result that as the wind speed rises up, the computed values of the heat exchanger thickness and the corresponding heat exchanger weight decline gradually, while the pressure drop on the liquid side and the heat exchanger's efficiency increase continuously. The maximum heat exchanger thickness is 116 mm, appearing at 10 m/s wind speed, and the pressure drop on liquid side is 341.5 Pa which meets the system pressure drop requirements.

The above optimization of liquid cooling systems is limited to the computed result of heat transfers and structural dimension and weight, and based on the hypothesis of steady working condition and thus no comprehensive conclusion can be draw for the dynamic property, power consumption and operating cost of

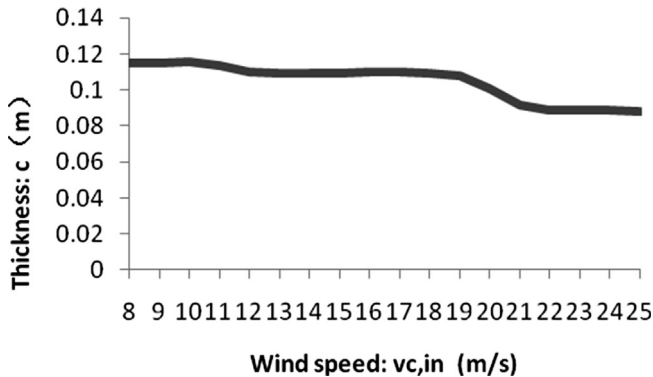


Figure 10: Relationship between wind speed and thickness of the heat exchanger adopting fin pair cc1 and ch1.

the wind turbine cooling system. In order to perform an exhaustive and objective optimization of the system, we will utilize tools such as computer-aided design, dynamic numerical simulation and so forth combining with the heat production data in the real-time wind turbine operation to launch a thorough and meticulous research. By doing these, we are able to render theoretical support to the future design of high-performance, reliable and economic wind turbines.

5 Future prospects on new type cooling system

With the wide application of wind energy at coastline area, the unit capacity of wind turbines increases greatly [22], which leads to a large rise of the heat production in gearboxes, generators and converters. The current liquid cooling system will no longer be sufficient to meet the cooling demands of wind turbines. Besides, the current cooling system has not taken full advantage of the ambient environment, such as high wind velocity, large solar energy density, etc. Therefore, there is a great potential to improve the operation economical efficiency. To solve the two problems above, some new cooling techniques for wind turbines are proposed in this section as follows.

5.1 Vapor-cycle cooling methods

From the theories of thermodynamics, all the current wind turbine cooling methods absorb heat by utilizing the specific heat capacity of the medium, while the vapor-cycle cooling uses the gasification latent heat of the boiling fluid to deliver the heat. As the gasification latent heat of the fluid is much larger than its specific heat capacity, the effect of the vapor-cycle cooling will be more obvious [24]. Therefore, the implementation of the vapor-cycle cooling technology is worthy of consideration. As shown in Fig. 11, its feature is that the system sets a vapor-cycle refrigerating engine outside the nacelle. During the operation, the cooling medium flows through the heat exchangers which is installed outside the gearbox, the generator, and the control converter successively,

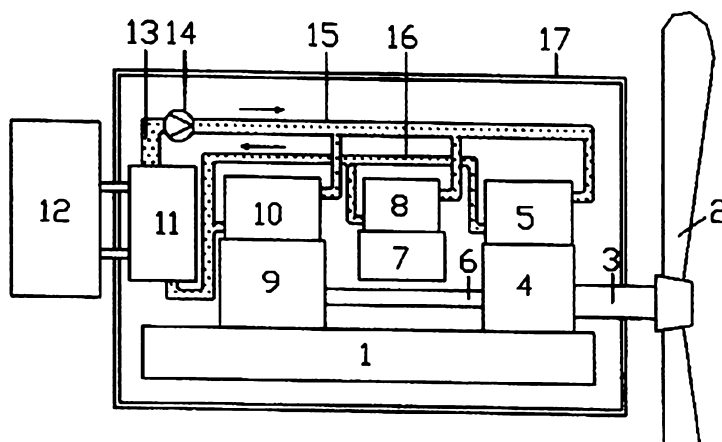


Figure 11: Structural diagram of the wind turbine adopting vapor-cycle cooling method: 1, saddle piece; 2, impeller blade; 3, low-speed shaft; 4, gearbox; 5, gearbox heat exchanger; 6, high-speed shaft; 7, control converter; 8, control converter heat exchanger; 9, generator; 10, generator heat exchanger; 11, cooling medium heat exchanger; 12, vapor-cycle refrigerating engine; 13, cooling medium; 14, circulating pump; 15, cooling medium inlet pipe; 16, cooling medium return pipe; 17, nacelle cover.

and take away the heat produced by these components. The heated cooling medium flows through an evaporator, getting cooled by exchanging heat with the refrigeration coolant circulating in the vapor-cycle refrigerating engine, and then perform the next round of cooling driven by circulating pump, which ensures that every component operates under a proper working condition. One thing worth mentioning is that the refrigerating engine can use bellows as connections among the cooling medium heat exchangers so that it will be more adaptable to the rotating working condition of the nacelle because of the change in wind direction during its running. The condenser of the refrigerating engine can be installed outside of the pylon in order to enhance convective heat transfer.

Comparing with the current forced air cooling and the liquid cooling method, the vapor-cycle cooling system introduces an extra cost of vapor-cycle refrigerating engine and additional power consumption for the cooling of the medium, however, it can adjust cooling capacity flexibly according to the cooling demands, and also can provide the optimal working condition for the wind turbine which paves the way for the next generation of high-power wind turbines.

5.2 Centralized cooling method

The current cooling solutions and the one discussed in Section 5.1 all aim at one single generating set. However, one with a complicated system is a prevalent issue, which leads to a huge difficulty for installation and maintenance, and, therefore, lowers down the operating reliability and the economical efficiency. Especially, with

the increasing unit capacity of wind turbines, the heat production in the operation procedure will increase sharply and the disadvantage mentioned above of the traditional stand-alone cooling method will be more acute. Hence, the centralized cooling method is taken into consideration. As shown in Figs 12 and 13, the feature of a centralized cooling system for wind turbines is that it sets a cooling unit in the wind power plant, providing centralized cooling capacity to every wind turbine in it.

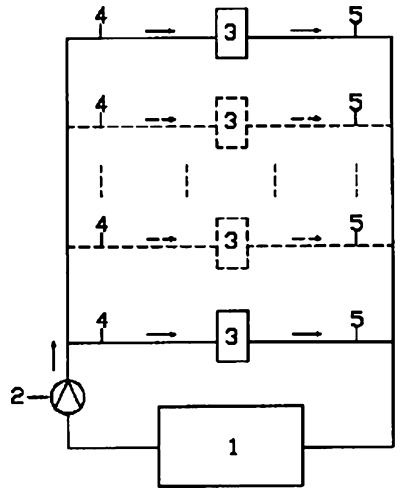


Figure 12: Schematic diagram of wind turbine centralized cooling system: 1, refrigerating engine; 2, circulating pump; 3, wind turbine; 4, cooling medium carrier pipe; 5, cooling medium return pipe.

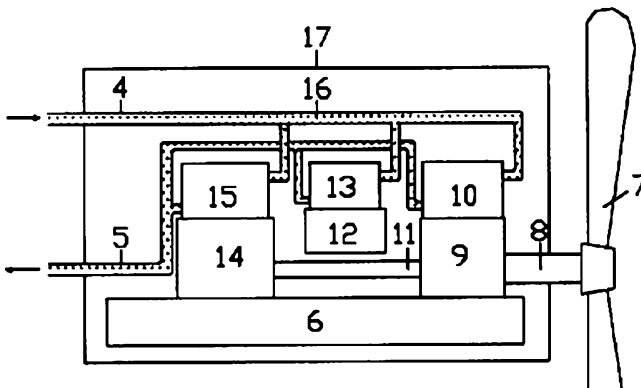


Figure 13: Structural diagram of wind turbine centralized cooling system: 6, saddle piece; 7, impeller blade; 8, low-speed shaft; 9, gearbox; 10, gearbox heat exchanger; 11, high-speed shaft; 12, control converter; 13, control converter heat exchanger; 14, generator; 15, generator heat exchanger; 16, cooling medium; 17, nacelle cover.

Similar with the wind turbine adopting vapor-cycle cooling method, the cooling medium runs sequentially through the heat exchangers outside the gearbox, the generator and the control converter, taking away the heat produced by these components. The heated cooling medium is then delivered to the refrigerating engine in the wind power plant through the cooling medium return pipe to get centralized refrigerated and once again delivered back to every wind turbine through the carrier pipe to perform the next round of cooling.

In a practical application, different types of air coolers or refrigeration units can be selected for the cooling unit according to the cooling demands of the generator. Compared with air coolers, refrigeration units are able to obtain lower cooling temperature. When the individual refrigeration unit cannot suffice to the cooling demands, multiple refrigeration units can be adopted; when the cooling demands are changed because of climate, season and other factors, they can be flexibly regulated by just changing the number of devices in operation. As to the wind power plant with a large-scale geographical area and a large number of generators, an alternative option is to set several centralized refrigeration units at different proper locations, according to the practical situation, to better satisfy the cooling demands and rationalize the distribution of the cooling medium delivery lines, aiming at obtaining high dependability and economy. With regard to wind turbines under low operating temperature, in order to reduce the cooling capacity wastage in the delivery of cooling medium, the system can adopt those pipe lines with good heat-insulating property and conduct some treatments of thermal insulation, such as coating the pipe with heat-insulating layers etc. The carrier and return pipes of the cooling medium can be laid out along with electric cables within the pylon so as to avoid corrosion of blown sand and rain to the pipeline. Besides, the joint of the cooling medium carrier and return pipe lines and the wind turbines can also be connected with bellows.

Compared with the forced air cooling and the liquid cooling systems, although the initial cost and the operating cost of the centralized cooled wind power generating system is higher, it has its own advantages, such as huge cooling capacity and flexible adaptability. Besides, the refrigeration units can aptly adopt various cooling manners according to the operating requirements of the wind power devices so as to suffice to the high-power cooling demands, which pave the way for the new generation of high-power wind turbine sets. Comparing to the vapor-cycle cooling method, this system simplifies the internal cooling devices of the wind turbine, and lowers the operating weight to make it suitable for the operation of wind turbines at a high altitude, which, thereby, eases the maintenance of the devices. In addition, when dealing with cooling demand fluctuation caused by changing of season, climate or other factors, no adjustments to individual wind turbines are required, but simply the adjustment to refrigeration units is needed.

5.3 Jet cooling system with solar power assistance

The cooling technologies and solutions mentioned above are all driven by electricity but the solar power as a clean energy from the atmosphere is omitted. This omission, to some extent, lowers the generating efficiency. Actually, the current heat-driven cooling technique is fairly mature. Because of these, the solar power jet cooling method can be implemented in the wind turbine cooling system.



As shown in Figs 14 and 15 [26], the features of a wind turbine adopting a cooling system with solar power jets include a solar thermal collector covering on the nacelle and a jet refrigerating engine with a secondary refrigerant circulation through heat exchangers of the gearbox, the control converter and the generator.

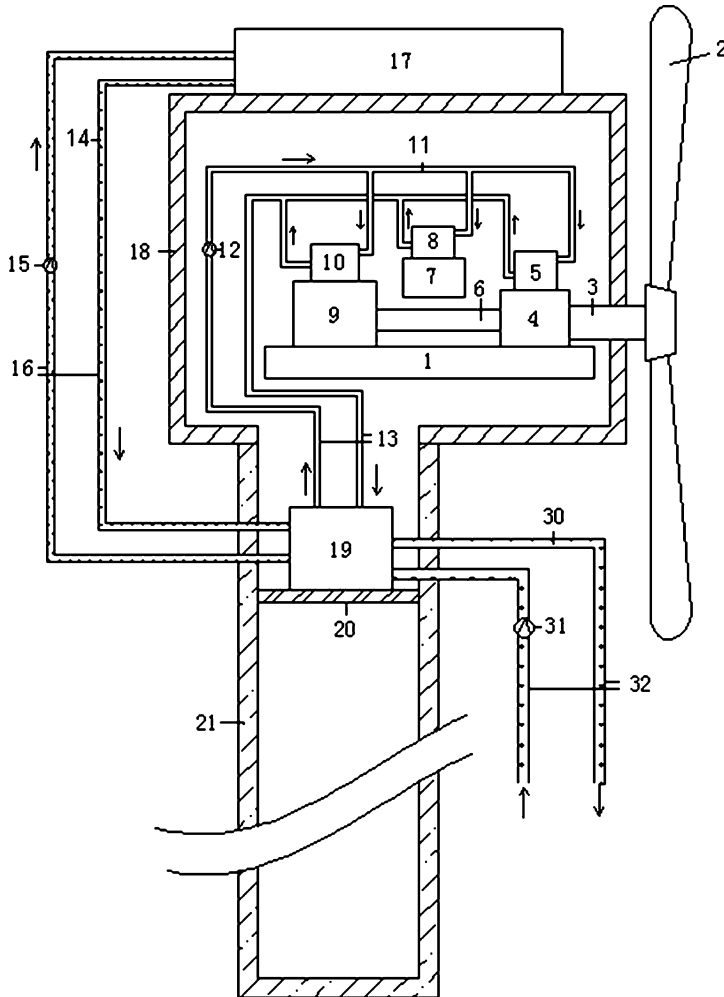


Figure 14: Schematic diagram of solar power jet cooling wind turbine: 1, saddle piece; 2, impeller blade; 3, low-speed shaft; 4, gearbox; 5, gearbox heat exchanger; 6, High-speed shaft; 7, control converter; 8, control converter heat exchanger; 9, generator; 10, generator heat exchanger; 11, secondary refrigerant; 12, circulating pump I; 13, carrier pipe of secondary refrigerant; 14, heat storage agent; 15, circulating pump II; 16, carrier pipe of heat storage agent; 17, solar thermal collector; 18, nacelle cover; 19, jet refrigerating engine; 20, platform of the pylon; 21, pylon; 30, cooling medium; 31, circulating pump III; 32, carrier pipe of the cooling medium.

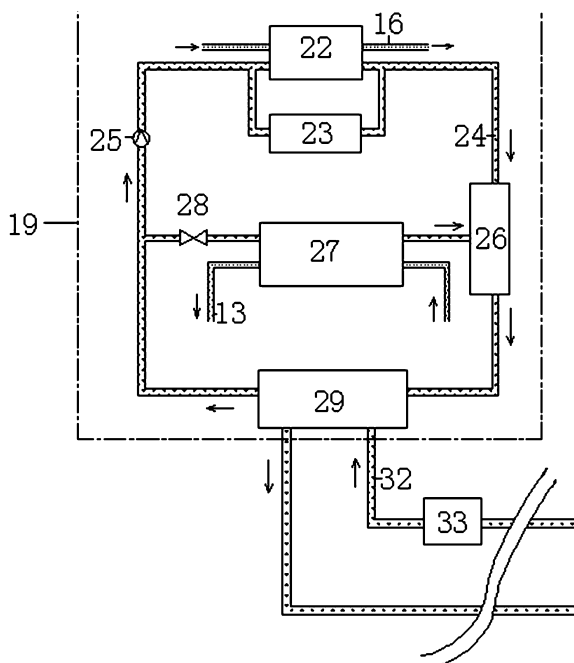


Figure 15: Schematic diagram of the solar power jet refrigerating engine: 22, heat accumulator; 23, auxiliary heater; 24, refrigerant; 25, circulating pump IV; 26, jet apparatus; 27, evaporator; 28, throttle; 29, condenser; 33, filter. The remaining symbols have been annotated above.

Similar to the wind turbine introduced in Section 5.1, during the operation, the secondary refrigerant sequentially flows through the heat exchanger outside the gearbox, the generator and the control converter, removing the heat produced by these components. The heated secondary refrigerant is then driven to the jet refrigerating engine by the circulating pump through the carrier pipes and performs heat exchange with liquid refrigerant in the evaporator. Finally the cooled secondary refrigerant is then delivered back to the above three heat exchangers to absorb heat. This circulation cycles to ensure the durable and secure operation of the wind turbine.

In the operation of the jet refrigerating engine, the solar thermal collector converts the solar energy into heat energy, leading to a rise of the heat storage agent in it. The heat is then delivered by the heat storage agent and stored in the heat accumulator. The heat-released heat storage agent flows back to the heat accumulator driven by a circulating pump, thus completes a circuit of solar energy conversion. Meanwhile, the refrigerant absorbs heat in the heat accumulator and gasifies and thus supercharges the pressure. The refrigerant is then ejected through the jet apparatus, leaving a low pressure close to vacuum at the jet tip. The low pressure steam refrigerant in the evaporator is thus drawn into the jet apparatus due to the pressure difference. The mixed steam refrigerant from the jet apparatus is then ejected into the condenser and performs heat exchange with the cooling medium

flowing through the condenser. The cooled refrigerant is shunted into two parts by pipelines. One of the streams flows back to the heat accumulator to complete the power cycle while the other passes through the throttle to the evaporator, where it performs heat exchange with the secondary refrigerant and gasifies, turning into a low pressure steam. So far a refrigerating cycle is completed.

It is worth mentioning that sea water or underground water can be used as cooling medium in the condenser. To prevent blockage resulting in bad cooling effect, a filter needs to be installed on the cooling medium carrier pipe on the way to the condenser. In the area where water is hard to reach, the cooling medium can be the other liquid processed by the seawater heat exchanger or the underground heat exchanger. No matter which conditions, for those components and pipelines submerged in water, effective anti-corrosion treatments should be implemented. Those treatments include choosing the resistant material, protective coating technology and cathodic protection technology. In the night or the abnormal working condition of the heat accumulator, an auxiliary heater can be used to heat the refrigerant flowing through to offset the energy shortage of the heat accumulator.

Comparing with the current wind turbine cooling system, the jet cooling system with solar power assistant possesses many advantages, such as lower power consumption, better cooling performance and environment friendly. Only the circulating pump and auxiliary heater need electricity support in the cooling system, which enables low electricity consumption of the whole system; while the solar power jet cooling method can obtain temperature below the ambient temperature, which will ensure the temperature in the optimal working condition. And the refrigerant in this system can be chosen from the non-chlorofluorocarbons substances (NON-CFC) which will be of great help to the environment protection. Besides, since the jet refrigerating engine has a simpler and lighter structure than other ones in the current technology, this merit will enhance the total anti-fatigue property of the nacelle; also because it is usually installed in the nacelle, which will avoid the corrosion caused by blown sand and rain, the working performance and life span will be effectively secured. Therefore, it can satisfy the highly efficient and dependable working requirements of the high-power wind turbine.

5.4 Heat pipe cooling gearbox

The three solutions mentioned above mainly focus on the entire cooling effect of all the heat producing components. On the other hand, considering different structural conditions and cooling demands of various components and using corresponding combinatorial solutions will possibly further enhance the operating economical efficiency, which is also a future trend for wind turbine cooling systems. Since the gearbox has a simple structure and an ample space for installation, a cooling solution adopting gravity heat pipe is proposed in this section while the generator and the control converter remain adopting a traditional liquid cooling system.

As shown in Figs 16 and 17 [27], the feature of a wind turbine system adopting a heat pipe cooling gearbox is that it has several apparatuses, including a gravity heat pipe connected with the gearbox to refrigerate the lubricating oil in it, a

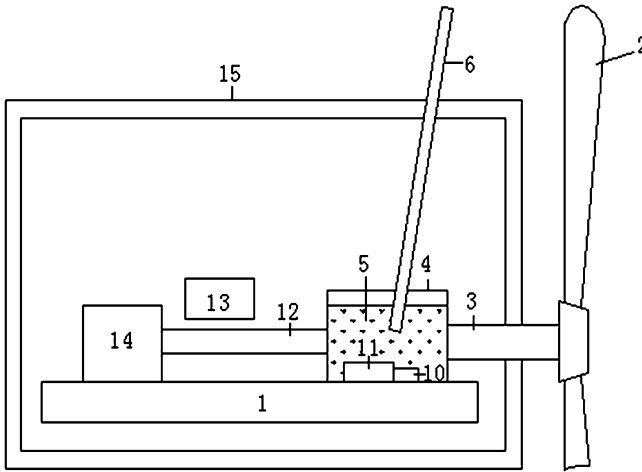


Figure 16: Schematic diagram of the wind turbine system adopting heat pipe cooling gearbox: 1, saddle piece; 2, impeller blade; 3, low-speed shaft; 4, gearbox; 5, lubricating oil; 6, gravity heat pipe; 10, temperature controller; 11, electric heater; 12, high-speed shaft; 13, control converter; 14, generator; 15, nacelle cover.

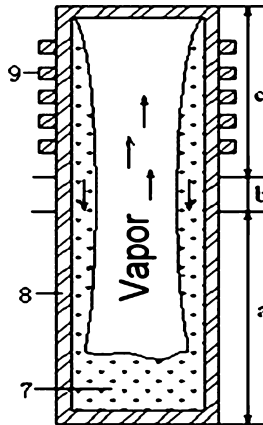


Figure 17: Schematic diagram of gravity heat pipe: 7, working substance; 8, shell of pipe; 9, radiating rib; a, evaporation zone; b, insulation zone; c, condensation zone.

temperature controller and an electric heater aiming at preventing extreme cold of the lubricating oil in winter. During the operation of the wind turbine, the heat produced by the gearbox is firstly absorbed by lubricating oil, and then delivered to the evaporation zone of the heat pipe. The working substance in the heat pipe evaporates because of heat absorption. The vapor ascends in the axial direction along the heat pipe, passing the thermal insulation zone, and then releases heat and

condenses in the condensation zone outside the nacelle. Finally the liquor condensate returns to the evaporation zone with the assistance of gravity, which begins the next evaporation procedure and so forth to perform effective cooling on the gearbox. In winter, in order to avoid getting extremely cold lubricating oil caused by the large cooling capacity of heat pipes, which is common in the northern cold area, the gearbox is installed with a temperature controller, performing real-time monitoring of the gearbox lubricating oil temperature. In addition, the heat pipe in the system can adopt inclination arrangement to ensure the liquor condensate returning to the evaporation zone smoothly, by which to ensure continuity and validity of the cooling system. Besides, in the operation, the number and distribution of heat pipes can be selected according to the real heat transfer capacity.

Compared with the current cooling system with a wind turbine gearbox and the above three solutions, the wind turbine system adopting a heat pipe cooling gearbox has many advantages to satisfy the wind turbine cooling demands, such as simple structure, self-driven, high heat transfer efficiency, low cost, easy to install and repair, small need on lubricating oil and so forth. Besides, it can keep the gearbox operating under the condition of optimum working temperature by selecting proper working substance in the heat pipe.

The wind turbine cooling systems introduced above are only limited examples of the future possible systems. With the development of the wind turbine technology, various cooling solutions will emerge. However, only those cooling systems with better cooling effect, higher economical efficiency and lower power consumption will be widespread in the future development.

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