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TOPICAL REVIEW

Vehicle Retarders: A Review

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ABSTRACT Under continuous braking and long slope braking conditions of high intensity for a long time, the temperature of the brake friction plate is extremely high, which leads to poor braking efficiency in the braking process, and even makes the braking force completely lost, More and more heavy-duty vehicles and high-speed transport vehicles are equipped with retarders. As an auxiliary braking system, a vehicle retarder can effectively maintain constant braking efficiency during vehicle braking. This paper discusses the development of HR (Hydraulic retarder) and ECR (Eddy current retarder) with the largest market share, working principle, installation mode, braking efficiency constant effect during use, application range, advantages and disadvantages, patent ownership, and technical difficulty. The technical demands and development trends of future retarders are summarized.

INDEX TERMS Heavy load vehicle, auxiliary braking, hydraulic retarder, eddy current retarder, constant braking efficiency.

I. INTRODUCTION

In conventional vehicles without retarders, the braking process relies on friction sheets and the friction resistance between tires and the ground to absorb braking energy. The test shows that when a 50T heavy truck runs on the horizontal roadside, emergency braking starts from 100 km/h until the vehicle is completely stationary. The temperature of the brake friction plate will rise sharply to more than 600°C in a very short time, the tire temperature exceeds 300°C, and the braking efficiency of the vehicle is completely lost [1]. When the vehicle brake disc continues to brake with high intensity for a long time, and the long slope and steep slope brake for a long time, it will lead to the explosion of the brake disc or wheel hub, and the tire temperature rise is too high to cause misfire and other malignant accidents. The main brake type of the vehicle has been developed from drum brake to disc brake, and the performance of the brake has been significantly improved; however, it still fails to meet the increasing braking force demand during normal driving of the vehicle [2]. The installation of a retarder is the best solution to effectively reduce the temperature rise of the brake in the process of vehicle braking [3].

Driving for a long time in the mountains of trucks and buses for braking, in order to solve the problem of brake temperature being too high, the tire temperature overrun, large trucks are usually equipped with a large water tank, the vehicle carrying current long slope condition, the water in the tank spray on the rim and tire, to achieve the purpose of cooling and maintaining a constant vehicle braking performance; the disadvantages of a vehicle equipped with a water tank are as follows: increasing the load of the vehicle and improving the fuel economy of the vehicle; in winter, the road with water freezes, and the vehicles behind it slip, resulting in traffic accidents. Spray-cooling water, serious waste of freshwater resources. There are also drivers down the steep slope of the long slope, reducing the speed very slowly, and extending the brake heat dissipation time method. However, extremely slow downhill speeds seriously affect the driving speed of the following cars in the same lane, and a very slow driving speed also greatly affects transportation efficiency. The limitations of traditional braking modes of vehicles are

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becoming increasingly obvious. The braking force generated by brakes alone can no longer satisfy the requirement for the constant braking performance of heavy-duty vehicles, and auxiliary braking devices are required to reduce the load of the driving brakes [4]. In addition to the relatively mature engine auxiliary brake device, more and more heavy duty vehicles are equipped with retarder auxiliary brake system, Engine braking is the use of engine drag action to slow down the speed, the engine has no traction on the car. In contrast, because the wheel rotation drives the transmission system, the idle engine has a counter-acting resistance to the car, and the lower the gear position, the more obvious the drag and the stronger the braking. The retarder auxiliary braking system works independently and is not affected by engine braking, However, when the retarder brakes, the engine cannot stop working, so the hybrid power transmission system is used in the braking process, which includes engine braking and retarder braking. Currently, HR and ECR are the most commonly used methods. The use of the retarder significantly improves the constant braking efficiency of the vehicle, and the vehicle can quickly respond to the braking requirements under dynamic braking conditions. The retarder assists the braking system, effectively reducing the use time of the brake under braking conditions, ensuring that the original braking system has the best braking efficiency, that the vehicle runs smoothly during the braking process, and that vehicle braking is safer [5].

II. DEVELOPMENT PROFILE AND RESEARCH STATUS

Germany's VOITH company produced the first HR in 1961; Fig. 1(a) shows VOITH HR, and many HR companies have emerged, such as Germany's ZF company, Germany's VOITH company, and the United States' General Motors. With their mature technology, these companies have become representative of the development level of the current automobile HR industry. European countries have enacted regulations requiring buses over five tons and freight cars over nine tons to be equipped with a retarder auxiliary braking system, and most of these vehicles are equipped with HR [6]. ALLISON developed HR in 1965 with braking torque applied directly to the drive shaft. The ZF company was the first to develop an integrated transmission and HR, the compact retarder is called Intarder, the so-called integral is to integrate the hydraulic retarder in the automatic transmission; the two use a set of hydraulic and cooling systems, making the design of the hydraulic and circulation cooling systems simpler, and the structure of the vehicle transmission system is more compact. The control system was designed to be better. Fig. 2 shows the development of the HR, whose braking torque and integration degree increase. American military off-road vehicles, armored tanks, and engineering vehicles are equipped with HR as auxiliary braking devices to operate with the main brakes. HR has been widely used in highway vehicles, buses, school buses specially used for transporting students, and some private cars [7]. Chai Yefei et al. [8]. proposed an integrated HR regulating device. The retarder in the patent has the characteristics of high safety, low cost, and long life. Mu et al. [9]. proposed a fixed-shaft power-shift transmission with HR. The transmission in the patent has the characteristics of flexibility in handling and prolongation of the brake and tire maintenance cycle. Han et al. [10]. proposed a control method for high-power HR. The retarder in the patent can solve the technical problems of the architectural design and function realization method of the electronic control software of a high-power HR. Shi et al. [11]. proposed a control method and device based on an ABS HR. The patent controls the HR through a control algorithm that can be applied to most car models. According to the brake pedal stroke output corresponding to the torque, achieving stepless control is suitable for flexible vehicle scenarios.

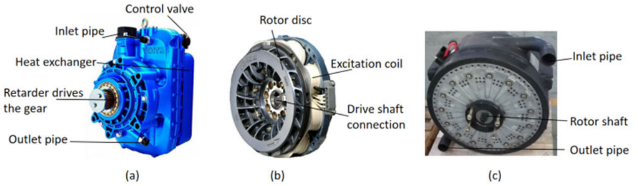

FIGURE 1. (a) VOITH HR (b) Air-cooled ECR (c) Liquid-cooled electromagnetic retarder.

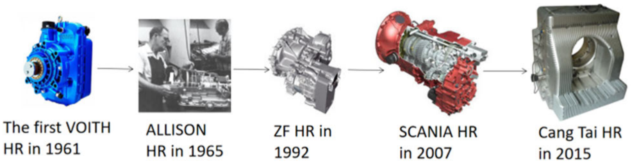
The first VOITH HR in 1961 → ALLISON HR in 1965 → ZF HR in 1992 → SCANIA HR in 2007 → Cang Tai HR in 2015

FIGURE 2. The development of the HR.

The French engineer STECKEL declared the world's first invention of ECR in 1903 [12]. In the 1930s, some European manufacturers realized the importance of using retarders on vehicles that often continuously brake on long downhill slopes in mountainous areas, and it was not until 1936 that the French company JOURDAIN MONNERET produced the world's first ECR [13], [14]. France TELMA purchased Raoul SARAZIN's patent for the ECR and began mass production of the ECR [15]. The use of ECR reduces the wear of brake shoes and wheel hubs, and improves the economic effect [16]. The cooling modes of the ECR include air and liquid cooling. The structure of the air-cooled ECR is relatively simple, but its heat dissipation effect is poor, and the braking torque thermal decay is serious; therefore, it cannot be widely used in heavy-duty vehicles [17]. Fig. 1(b) shows the air-cooled ECR of TERCA Company. The structure of a liquid-cooled ECR is complex, but its heat dissipation effect is excellent, and its braking efficiency is constant, making it suitable for use in heavy-load vehicles [18]. Jung et al. [19]. adopted a voltage control method to recover the electric energy generated by the electromagnetic retarder and converted the mechanical energy generated during the braking process into electric energy to charge the energy storage device to improve energy efficiency.

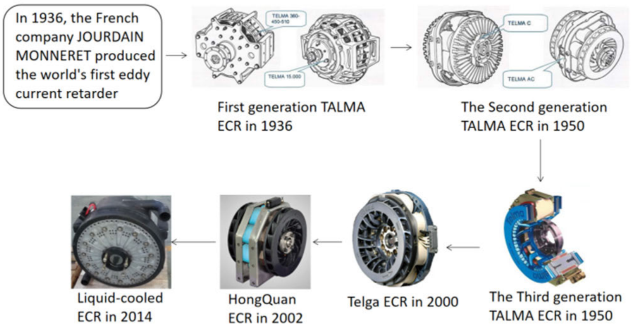

FIGURE 3. The development of ECR.

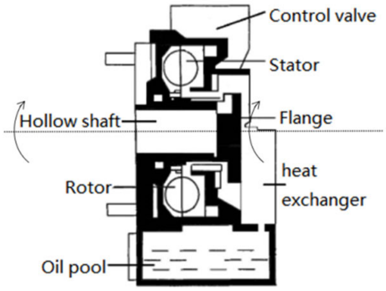

FIGURE 4. Profile of VOITH HR [28].

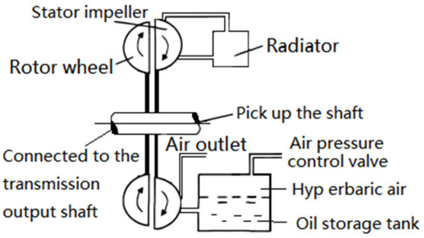

FIGURE 5. Working principle of HR [7].

Ding et al. [20]. proposed an automobile eddy current retarding system. The retarder in the patent has the characteristics of fast heat dissipation, high reliability, and a long service life. Tian et al. [21]. proposed an eddy-current retarder excited by a toothed coil. The retarder in the patent has the characteristics of high efficiency, small space occupation, low reluctance, and high power density. Zhang et al. [22]. proposed an ECR. The retarder in the patent has the characteristics of a high space utilization rate and increased magnetic flux ratio. Zhen [23]proposed a water-cooled self-excited eddy current retarding device. The retarding device in the patent avoids the winding of water-cooled pipes, filters impurities in cooling water, and keeps the water-cooled channels unobstructed. Guo et al. [24] studied a new type of self-excited liquid-cooled bridge integrated retarder and used the finite element analysis method to analyze the eddy current braking torque, thermal attenuation of braking torque, and no-load loss torque of the liquid-cooled bridge integrated retarder. The results indicated that the eddy current braking torque reached 2592 N·m at a speed of 1000 rpm. After 12 min of continuous braking, the braking torque decreased by 15.5%. Zhang et al. [25] used the finite element method to analyze the electromagnetic field and braking performance of a self-excited liquid-cooled electromagnetic retarder, and used the finite volume method to numerically simulate the transient flow field and thermal field of the retarder. The results showed that the braking torque can reach 1600 N·m, and the thermal decline of the braking torque was below 5% during continuous operation. Ding et al. [26] designed an electromagnetic liquid-cooled retarder control system to satisfy the high current requirements of the retarder. When the terminal voltage of the battery is 24.6V, the currents driving the excitation coil are 50A, 100A and 150A, respectively, in the first, second, and third gear modes, and its braking torque is up to 6000 N·m. Fig. 1(c) shows the physical diagram of the liquid-cooled electromagnetic retarder. Compared with traditional ECR, the liquid-cooled electromagnetic retarder has the advantages of no power consumption and low attenuation [27]. Fig. 3 shows the development of eddy-current retarders, which have become mainstream.

III. WORKING PRINCIPLE OF RETARDERS

A. WORKING PRINCIPLE OF HR

The stator of the HR is integrated with the housing and mounted either at the rear end of the transmission or the rear end of the frame (depending on the mounting method). The rotor is connected to the drive shaft by a hollow shaft, and the blades are cast on both the rotor and the stator. Fig. 4 shows the section view of the FOITH HR.When the HR works, through the operation of the control valve, the oil tank to apply a certain pressure to the working chamber is filled with working fluid, the rotor rotation drives the working fluid flow, the stator torque is applied to the stator, and the reverse moment of the stator becomes the braking torque of the rotor, the size of the braking torque value depends on the fluid volume in the working chamber, the pressure (the control valve set the braking intensity of the gear) and the rotor speed [29], Fig. 5 shows the working schematic diagram of the HR [30]. The kinetic energy of the vehicle is converted into heat energy of the liquid in the working chamber, resulting in an increase in the temperature of the working fluid. The working fluid is also introduced into the circulating flow of the heat exchanger, and the circulating cooling water dissipates the heat through the engine cooling system. When slow action is relieved, the control system eliminates the resistance of the rotor by releasing the working fluid. The rotor and stator are usually inclined blades at 30° or 45°, and the torque coefficient of the rotor is approximately 3–10 times that of the hydraulic coupling of the radial blade of the same wheel cavity [31]. For a vehicle with hydraulic transmission, the oil pool, oil pump, heat exchanger, and working fluid can be omitted; therefore, the hydraulic transmission vehicle is very suitable for installing the HR. In addition, the HR

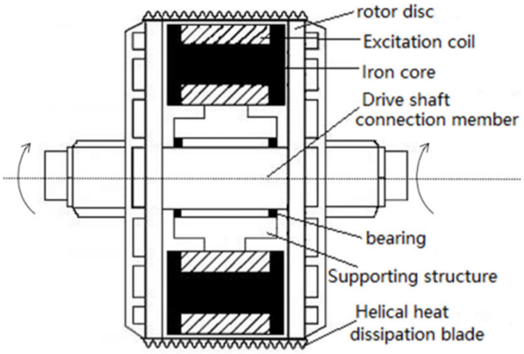

FIGURE 6. **Traditional air-cooled ECR [28].**

electronic control system is compatible with the ABS system. When the ABS is operating, the retarder stops operating [32].

B. WORKING PRINCIPLE OF ECR

At present, there are air- and liquid-cooled ECR in the market. Because air-cooled ECR has no obvious cooling effect, high thermal decay, and low reliability, it has been gradually phased out. There is little research on air-cooled ECR, and there are only three patents for air-cooled ECR on the official website of the State Intellectual Property Office. Liquid-cooled ECR and air-cooled ECR work in a similar manner, but the method of heat dissipation is different [32].

1) WORKING PRINCIPLE OF AIR-COOLED ECR

During operation, the energized coil generates a magnetic field on the stator, forming a ring magnetic circuit, and the magnetic circuit is complete. When the rotor rotates, its inner surface cuts the magnetic induction line, generating an alternating magnetic field and eddy currents. The drive shaft drives the rotor to rotate together, and the rotor cuts the magnetic field line generated by the stator to generate the braking torque [33]. Owing to the existence of a certain resistance in the rotor, the generated eddy current is constantly converted into heat energy in the form of electrical energy. The heat generated on the rotor can be distributed into air through air cooling. The outer diameter of the rotor was opened with a helical tooth-shaped heat sink, and the helical tooth-shaped heat sink blade on the rotor acted as a fan with the rotation of the rotor to accelerate heat emission [34]. As shown in Fig. 6, the traditional air-cooled ECR stator is equipped with a single coil, the salient pole rotor on the heat sink for cooling by air convection on the retarder. However, the cooling efficiency is extremely low, and it cannot disperse heat in a short time, leading to poor braking performance.

2) WORKING PRINCIPLE OF LIQUID-COOLED ELECTROMAGNETIC RETARDER

The magnetic field generated by two adjacent energized coils sends two magnetic field lines of opposite polarity and forms a loop. Lenz's law indicates that in a closed circuit, an induced current is generated when the magnetic flux passing through the circuit changes, and the magnetic field of the induced current always hinders the change in the magnetic flux induced by the current [29]. If the coil is on the excitation current, the magnetic core and the core flux rate change, so that the rotor plate eddy current [35] on the rotor coil in the magnetic field force with the current role, the role of direction, and the rotation of the rotor disc in the opposite direction, so that the generated ECR braking torque. The braking torque is affected by the magnitude of the excitation current; the greater the excitation current through the coil, the stronger the magnetic field and the greater the braking torque. Fig. 6 shows a schematic of the structure of the liquid-cooled ECR. As shown in Fig. 7, the engine power is transferred to the retarder through spline sleeve A, and in the retarder, the power is transferred to spline sleeve B through the rotor shaft, which becomes the power output [36]. The retarder transfers the output power to the main reducer of the vehicle, thereby creating a braking force on the vehicle. From the perspective of energy conservation, in the process of vehicle braking, the retarder converts the kinetic energy of the vehicle braking process into heat energy through the rotor, and realizes the consumption of kinetic energy in the process of vehicle braking [20]. Fig. 8 shows the control system structure of the liquid-cooled electromagnetic retarder. When the vehicle slows down, the controller supplies power to the excitation coil and the retarder starts to work. The hand-dial switch adjusts the current to control the retarder braking torque.

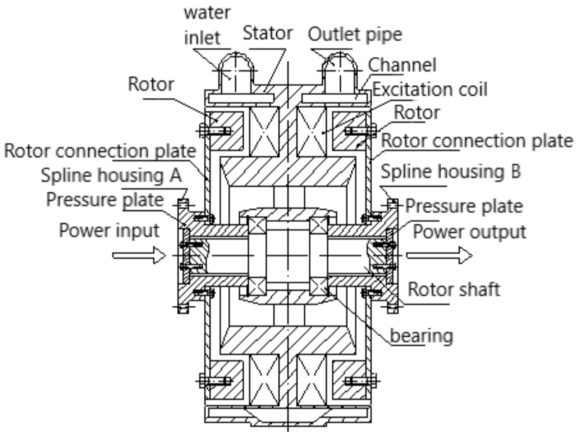

FIGURE 7. **Liquid-cooled electromagnetic retarder.**

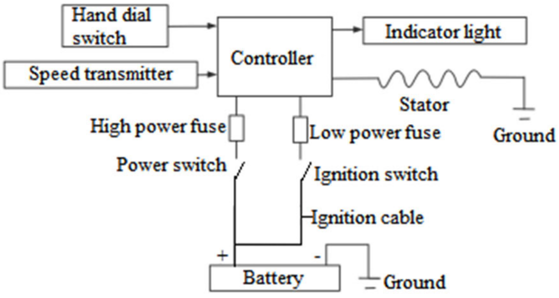

FIGURE 8. **Liquid-cooled electromagnetic retarder control system.**

TABLE 1. Comparison of the advantages and disadvantages of the installation position of the HR.

Installation position	advantages	disadvantages
Series installation	Integrated with the transmission, compact structure, large radial size, can provide large braking torque, easy modification.	Occupy a large space, can not install power take off.
Series independent installation	Independent installed between transmission shafts, independent oil supply system, easy after modification.	The drive shaft needs to be modified.
Parallel installation	Compact structure, light weight, and easy installation	To be customized according to the characteristics of the gearbox, applicability is high, the gearbox needs to be modified.

IV. ANALYSIS OF APPLICATION OF RETARDER IN DIFFERENT VEHICLES

A. INSTALLATION MODE

1) INSTALLATION MODE OF THE HR

The retarder is generally installed in the transmission system, and different installation methods have different requirements for the vehicle, such as the retarder installed in the drive shaft, which will cause the overall rigidity of the drive shaft to decline, which has higher rigidity requirements for the drive shaft. Any mounting method slightly hinders the power output of the drive system because it increases the friction between the power output gear and drive shaft. The HR is installed in three ways: series, series, independent, and parallel. ① In series installation, the HR is installed between the drive shaft and the transmission. Fig. 9(a) is a schematic diagram of the series installation structure, which is divided into two types: front and rear, where the front placement does not need the speed of the gear and can obtain a higher braking torque, but the shift will produce power interruption and impact. The braking torque of the rear mode directly acts on the transmission shaft of the vehicle, and there is no power interruption phenomenon when the vehicle shifts, but the braking ability is weak in low gear, which often requires a speed-up gear stage, and the series installation mode occupies a certain axial space. ② During series-independent installation, the HR is installed in the middle of the transmission shaft, which requires redesigning the transmission shaft. Fig. 9(b) shows a schematic of the series-independent installation structure. ③ Parallel installation is integrated with transmission to transmit power through gears. Fig. 9(c) shows a schematic of the parallel installation structure.

Table 1 Comparison of the advantages and disadvantages of HR installation positions. Through comparison and analysis of three installation methods of HR, it can be seen that for tandem type HR, It requires plenty of room on the beam at the rear end of the vehicle's gearbox to install the retarder, which is suitable for vehicles with loose body space, such as heavy trucks with wide chassis space. But the series retarder cannot be installed with power takeoff, so some engineering vehicles are not suitable for the series HR. The parallel installation of HR has the advantages of compact structure, light weight, less space, suitable for the use of vehicles with small body space, mainly passenger cars, light trucks and special purpose vehicles. The freestanding liquid buffer is located in the middle of the girders,and is suitable for any vehicle.

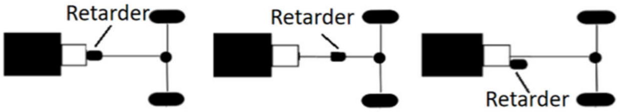

FIGURE 9. (a) The series-type installation (b) The series-connected independent installation (c) The parallel-type installation.

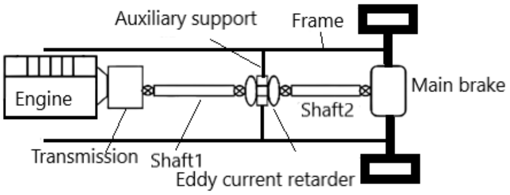

FIGURE 10. ECR is mounted on the drive shaft.

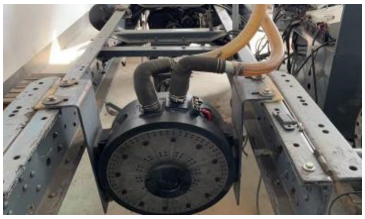

FIGURE 11. Test bench tandem ECR.

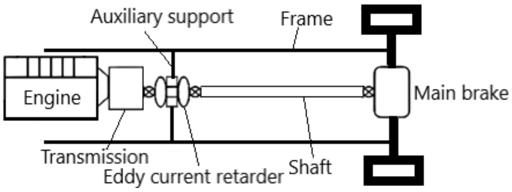

FIGURE 12. ECR is mounted on the transmission.

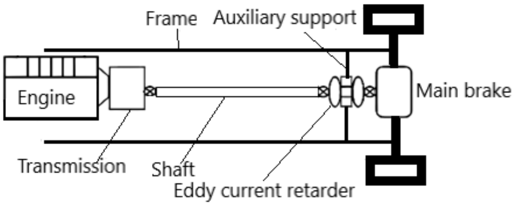

FIGURE 13. ECR is mounted on the reducer housing.

2) INSTALLATION MODE OF THE ECR

The ECR can be installed in three ways: ① Install the ECR can be installed on the drive shaft, and the structure diagram is shown in Fig. 10. The ECR of this structure has

TABLE 2. Advantages and disadvantages of ECR installation position analysis and comparison table.

Installation position	advantage	disadvantages
In series on the drive shaft	Relatively independent, easy to maintain	The drive shaft should be modified
Rear end of transmission	The rigid connection with the transmission has little vibration, high reliability and is not limited by its own weight	Need to redesign the transmission rear end structure
Front end of main reducer	Transmission, clutch disassembly convenient, power assembly is not affected	The main speed reducer structure needs to be modified

an independent structure, replacing the original car's long drive shaft with two short drive shafts and shafts 1 and 2. No changes were made to the transmission and rear axle; therefore, the retarder with this structure is suitable for the rear-mounted and front-mounted markets. Fig. 11 shows the tandem ECR on the test bench. ② The ECR was installed at the rear end of the transmission, and its structure is shown in Fig. 12. With this structure, the power input shaft of the retarder is directly connected to the transmission output shaft. The rear-end structure of the transmission needs to be redesigned, so the retarder with this structure cannot be applied to the rear-mounted market of vehicles. ③ The ECR is installed on the main reducer case, whose structural schematic is shown in Fig. 13. The power output shaft of the retarder is directly connected to the power input shaft of the main reducer of the vehicle, and the main reducer structure needs to be redesigned, so this form of retarder cannot be applied to the front installation market of the vehicle.

Table 2 presents a comparative analysis of the advantages and disadvantages of the ECR installation positions. The table shows that by installing the drive shaft, the ECR on the retarding device is independent and easy to tear open, so all vehicles are suitable for installation; the installation after the transmission side, the front end, and the main reducer retarder to be installed according to the specific vehicle size; and some of the smaller passenger cars and light trucks are not suitable for the installation of Fig. 12 and 13. A bus with a large interior space and rear-mounted rear drive is ideal for installing Figs. 12 and 13.

B. APPLICABILITY ANALYSIS

Fig. 14 shows a radar chart of the evaluation indices of HR and ECR. The performance indicators of the two retarders are clear.

Table 3 shows the evaluation and comparison table of HR and ECR. The braking torque, braking reaction speed, low-speed response, and disadvantages of the two retarders were compared.

Fig. 14 compares the two parameters in terms of braking torque, response speed, energy-saving effect, light weight, continuous braking ability, reliability, and price. It can be seen that the HR performs well in terms of braking torque, lightweighting, energy saving effect, continuous braking ability, and reliability. ECR has an absolute advantage in three main parameters: price, speed response timeliness, and braking force output at low speeds. Combined with Fig. 14 and Table 3, it can be seen that HR and ECR have their own advantages. Different working principles inevitably result in varying effects. Vehicles with different uses have different retarder requirements. The biggest advantage of HR is that the braking torque is large, but at low speeds, its braking force fails, so it is not suitable to be equipped with vehicles that often run at low speeds. The HR has high-speed deceleration, small size, transmission integration, light weight, and no wear during operation, and is suitable for installation in heavy vehicles, such as heavy trucks, large trucks, and other vehicles, owing to its large mass at high speed or long steep slopes where inertia is high and braking torque is required.

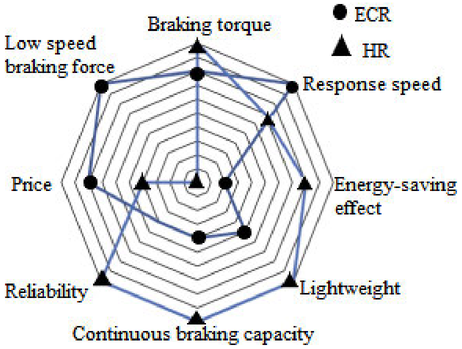

FIGURE 14. HR and ECR evaluation index radar chart.

The main benefits of the ECR are its quick response time, good low-speed braking force, and ready-to-use nature. Its low-speed braking force, in particular, compensates for HR's low-speed failure of the HR, making it suitable for installation in buses and cars. At present, the maximum braking torque of a liquid-cooled electromagnetic retarder in the market can reach 6000 N·m. The maximum braking torque reaches the maximum braking torque value of HR. An increasing number of mine cars and trucks driving in the Yungui Chuan area for a long time have been installed with liquid-cooled electromagnetic retarders, which greatly improves the safety of vehicle braking.

V. ANALYSIS OF APPLICATION OF RETARDER IN DIFFERENT VEHICLES

A. STUDY ON THERMAL MANAGEMENT SYSTEM OF HR

The viscosity of the liquid medium in the working chamber of the HR decreases with increasing temperature, resulting in a decrease in the braking force [19]. Liu et al. [37] used computational fluid dynamics (CFD) to capture the braking performance, internal flow field, and fluid structure interaction of the HR, and found that the reduction in liquid viscosity could effectively inhibit the generation of eddy currents, thus effectively reducing the energy loss near the wall.

TABLE 3. Evaluation and Comparison of hydraulic reducer and ECR.

Classification of retarders	Braking torque	Brake response speed	Low speed response	Advantage	Disadvantages
HR	The braking torque depends on the amount of fluid in the working chamber, the pressure and the speed of the rotor, and is proportional to the fifth power of the effective diameter of the working chamber.	It takes 2.5s to achieve the braking effect.	Low speed failure, no braking torque.	①Suitable for long slope, steep slope terrain, light weight;②Small power consumption, durability, high reliability;③It will not produce high temperature because of long time operation;④No electromagnetic interference, large braking torque;⑤High speed down, small size, can be integrated with transmission.	Its high price is twice that of ECR, and it has a long lag time of engagement and disengagement, power loss, and a slow response time when not working.
ECR	The braking torque depends on the inner and outer diameter of the rotor disc, stator material, permeability and stator excitation coil resistivity, and is proportional to the 1/2 power of the rotating speed	The whole process is about 40ms.	Low speed response is perfect, full speed effective.	①The brake load of the vehicle is eased;②Low speed braking force is strong; ③The braking torque is easy to control;④No wear and tear, high economic efficiency.	It is greatly affected by the ambient temperature. Large volume and high power consumption.

Through a comparative analysis of fluid-structure coupling (FSI) and heat-fluid-structure coupling (TFSI), it was found that the deformation and equivalent stress were significantly increased compared with the original simulated conditions owing to the thermal stress, and the stress damage of the HR shell was increased. Liu et al. [38] studied and developed an integrated cooling and evaporation system for HR, which makes the cooling water contact the conveying medium through the stator wall, and the cooling water can quickly change the flow rate with the thermal change of the retarder to keep the oil temperature stable. Liu et al. [38] first established the flow state of the transmission medium in a retarder under specific working conditions and analyzed the flow rate of the transmission medium under different radii of rotation. The integrated cooling and evaporation system was then designed, as was the heat transfer model. The temperature stability of the transmission medium and flow characteristics of the cooling medium were analyzed under different working conditions. It is found that The optimum working temperature of the transmission medium is in the range of 80°C ∼ 120°C. Compared with the traditional plate-fin heat exchanger, the heat dissipation capacity of the retarder is increased by 100 ∼ 200%, and its stability and durability are better. Yuan et al. [39] used the FLUENT software to numerically simulate the internal temperature field and flow field of a retarder under different rotor speeds and fully filled conditions. Fig. 15 shows the temperature distribution cloud diagram of the open HR. As can be seen from the figure, open working cavity hydraulic retarder temperature ranges from 333 to 369 K, 60 ∼ 96°C. In general, the temperature field distribution in the cavity exhibits the following characteristics: the temperature between the inner and outer edges of the rotor and the inner edge of the stator is low, and the temperature between the inner edge of the rotor blade and the outer edge of the stator is high.

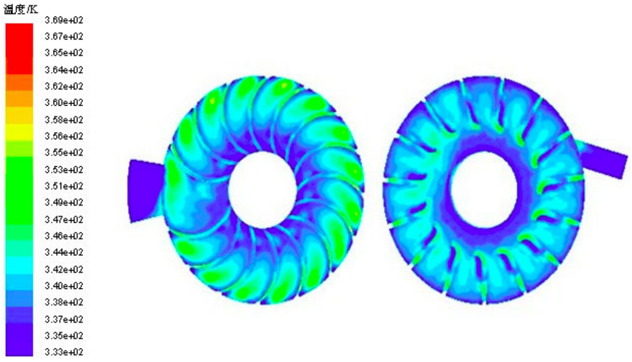

FIGURE 15. The temperature distribution cloud diagram of an open HR [39].

The traditional HR cooling system transfers heat to the circulating coolant, which is then dissipated by the engine cooling system. Wang et al. [40] studied the cooling system of an HR with an organic Rankine cycle. The organic medium transmits heat together with the working fluid of the HR in the Rankine cycle, which not only reduces the thermal load of the engine cooling system, but also improves the thermal stability of the HR. The preset Rankine cycle parameters were used to analyze the characteristics and power consumption of the cooling system under various HR working conditions. Compared with the traditional HR cooling system, the organic Rankine based HR cooling system takes up more space, but it can effectively reduce the thermal load of the engine cooling system, improve the thermal stability of the HR, reduce energy consumption, and be more economical.

The methods to improve the cooling effect of the HR are as follows: reducing the viscosity of the working liquid, changing the structure of the circulating liquid channel inside the retarder, changing the flow characteristics of the cooling medium, changing the type of the working medium, etc.

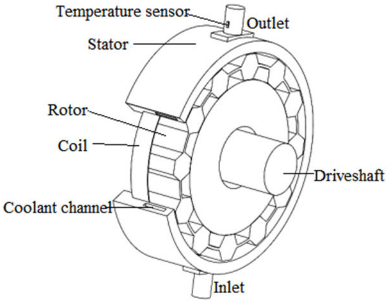

FIGURE 16. **Liquid-cooled and flywheel-type ECR [29].**

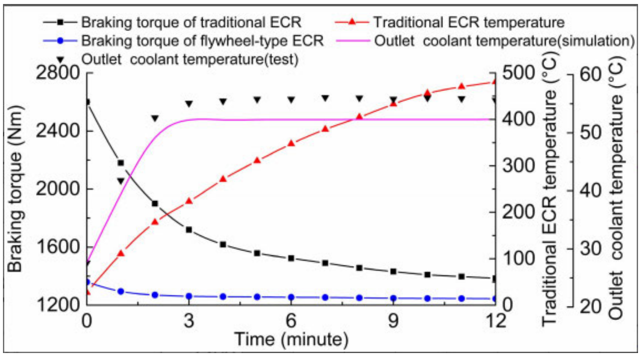

FIGURE 17. **The relationship between temperature and braking torque of ECR during continuous braking [29].**

B. STUDY ON THERMAL MANAGEMENT SYSTEM OF ECR

The biggest problem faced by the ECR is that the high temperature during continuous braking leads to a decrease in braking torque and seriously affects the safety performance of vehicle braking. Aiming at the problems of thermal attenuation and low power density caused by the continuous braking of a traditional ECR, Ye et al. [29] proposed a new liquid-cooled and flywheel-type ECR. Fig. 16 shows the structural diagram of the liquid-cooled and flywheel-type ECR. It is assembled between the engine and clutch to improve braking power density and maintain the retarder at a low working temperature. Based on the finite element method, the transient electromagnetic field of the ECR was solved and the braking torque characteristic curve was obtained. The thermal fluid coupling field was analyzed based on the fluid dynamics method. The structural parameters of the rotor gear were optimized. Fig. 17 shows the relationship between the temperature and braking torque of the ECR during continuous braking. The results show that the braking torque of the new ECR increases and the thermal decay ratio decreases. The service life of retarders is improved, and the braking effect of retarders operating at low temperatures is better.

Research on the heating characteristics of the ECR is conducive to the layout and parameter design of the liquid cooling channel of the retarder body. Ji et al. [41]designed an integrated ECR system. The thermal and magnetic coupling characteristics were studied, the variation rule of the auxiliary brake torque output affected by the retarder's body temperature was analyzed, and the heating characteristics of each part of the retarder were obtained. The results show that if the heat source is concentrated on the inner side of the stator of the ECR, the braking torque is reduced. If the liquid cooling channel is arranged near the inner side of the stator, the temperature of the stator can be effectively reduced and the braking time can be prolonged. In view of the heating phenomenon of ECR, Feng et al. [42] proposed a special oil cooling system, calculated the flow rate of the cooling oil, and used FEM to analyze the braking performance. The results indicate that the cooling system can effectively reduce the operating temperature of the ECR. Jiao [43] analyzed the steady-state thermal field of the stator. Fig. 18 shows the distribution diagram of the stator thermal field. The results showed that the stator temperature increased along the flow direction. The high temperature was concentrated in the heat source area. An increase in the stator temperature results in a decrease in stator conductivity. The eddy current generated on the stator will be reduced owing to the decrease in electrical conductivity, and the average temperature of the heat source region was 235.134°C.

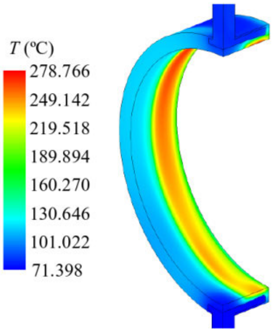

FIGURE 18. **The distribution of the stator thermal field [43].**

Li et al. [44]proposed a type of stator and excitation coil that uses water cooling. The ECR coil of the stator temperature field and the temperature field are established, and many transient electromagnetic field coupling and two-way data transmission models are analyzed, including the retarding device in the process of continuous braking performance owing to the influence of the system. The error gradually increases from 9.7% to 12.4%, but with the new stator water-cooling ECR and the stability of the excitation coil temperature, the error decreases. braking torque test values of the thermal decay rate were 20.3%; the magnetic thermal coupling method analysis of braking torque simulation values of the thermal decay rate was 15.9%; casting defects and the thermal deformation of the rotor were the main reasons for the error. Tian et al. [45], [46] studied the influence of heat on retarder deformation during operation. Based on the principle of eddy current braking and the current skin effect, they proposed a new heat dissipation method to directly cool the heating surface of the eddy current brake and developed a prototype of a new internal liquid-cooled eddy current brake with better heat dissipation. The results showed that when the retarder worked for a long time, the stator deformed because of high temperature. The maximum radial deformation of the stator inner ring was 0.54 mm. The heat dissipation efficiency of internal liquid cooling was better than that of external liquid cooling. Water is a better coolant than oil for heat dissipation. Gao et al. [47] proposed a type of consideration of the current decline in the magnetic thermal coupling model, the finite difference method to calculate the temperature distribution of the stator and the coil, the heat conductivity is analyzed, the decrease in the permeability of braking torque, and the influence of thermal decay. The results showed that the conductivity of counter-rotating torque attenuation is minimal, followed by the current. Liu et al. [48] proposed that the vehicle braking load must be shunted through the auxiliary braking device during the continuous braking process; only in this way can the thermal attenuation of the main braking system be avoided, and the temperature increase can also be reduced by increasing the surface area and the equivalent heat convection coefficient. Mei et al. [49] pointed out that traditional air-cooled ECR have limited cooling capacity, low thermal decay, and low reliability. A water jacket was set outside the eddy current zone to control the temperature of the ECR by adjusting the circulating water flow in the circuit, which also reduced the thermal decay of the ECR.

It can be seen that the thermal attenuation of ECR is still a big problem. The form of heat dissipation is from air cooling to liquid cooling, and then to the combination of air and liquid cooling. Currently, research on the heat dissipation of the ECR focuses on the heat dissipation structure, heat dissipation form, and flow characteristics of the coolant and cooling medium. In terms of the heat dissipation effect, water is better than oil as a coolant.

VI. FUTURE RETARDER TECHNOLOGY REQUIREMENTS

Innovation is the road to sustained development in all industries. Future retarder products must have a high level of intelligence, compact size, and better performance [50]. In the future intelligent retarder technology upgrade, with the development of computer technology, retarders will gradually develop in the direction of electronics and intelligence. With users' increasingly high-cost performance requirements for retarders and the introduction of a series of strict product standards for retarders, internal reorganization, mergers, integration, and survival of the fittest competition in the industry are unstoppable trends [52]. The following three technological trends will primarily drive retarder development in the future: braking efficiency constant technology, low loss technology, and energy recovery technology.

A. BRAKING PROCESS BRAKING EFFICIENCY CONSTANT TECHNOLOGY

The steadiness of braking efficiency is the most fundamental evaluation index of vehicle braking performance, and is an important index for measuring the thermal decay resistance of the brake. After a long braking time, the temperature of the brake friction plate is extremely high, and the friction factor of the friction material decreases, resulting in a reduction in braking efficiency. Constant braking efficiency technology integrates a retarder into the braking system to cooperate with the brake and reduce the frequency of brake use to ensure that the braking system has the best braking efficiency under braking conditions. In addition, it is necessary to improve the material of the brake friction plate and the structure of the brake to reduce the thermal decay performance of the brake and maintain a constant braking efficiency.

B. LOW-LOSS TECHNOLOGY

Low-loss technology has been developed for use in HR. In the non-braking process of the vehicle, that is, when the rotor is idle, there is some air in the retarder, and the braking torque generated at this time is air loss. According to the braking principle of the HR, the higher the rotor speed, the greater is the braking torque, which seriously hinders the acceleration effect of the vehicle under normal driving conditions. At present, there are integrated air loss reduction mechanisms in non-braking conditions that significantly reduce air loss. Zhao et al [51]. carried out a numerical study on a rotary hydraulic damper, which is very suitable for application in vehicle engineering. Rotary hydraulic dampers can be considered as a structure to reduce air loss because it has a closed inner cavity, the circumference is an irregular cross-section filled with damping grease, and the shell or the inner core rotates around, driving viscous damping grease movement, resulting in circumferential shear force. For serially mounted retarders, the damper can be integrated with the retarder on the gearbox, which means that the damper and the HR use the same working medium and generally use a higher viscosity oil to generate damping. When the rotor of the HR is idle, the generated braking torque acts on the rotating hydraulic damper to form a buffer effect, which not only reduces the air loss of the HR but also increases the braking torque when the HR is working.

C. ENERGY-RECOVERY TECHNOLOGY

When the retarder operates, most of the kinetic energy is converted into heat energy, which is discharged into the air and causes a large amount of energy waste. Energy recovery devices can be used to collect energy for secondary utilization to supplement the energy output of the ECU. At present, there are relevant studies on energy recovery retarders. If energy recovery is efficient, the economic benefits can be significant [53].

VII. CONCLUSION

The installation and use of a retarder can solve the problem of constant braking efficiency and load on the vehicle brake to a certain extent, which is called the ''ideal third brake'' in academic circles. In this paper, the structural principles and research status of retarders are reviewed, the advantages and disadvantages of the HR and ECR are evaluated from the perspective of using retarders, and the research direction of key technologies of retarders is further predicted from the perspective of technical challenges faced by retarders.

(1) It is still an important challenge for vehicles to simultaneously reduce the braking time and obtain the most significant braking effect at the same time. The use of a retarder can effectively alleviate the heat load of the brake, not only prolonging the service life of the brake but also ensuring vehicle safety. If the combination of retarders and brakes can be reduced, simplified, and optimized using intelligent control technology, there will be better application prospects in the future.

(2) When the retarder works for a long time, the high temperature generated inside the retarder cannot be dispersed in time, which seriously affects the braking effect of the retarder and causes significant safety hazards. At present, the cooling system of retarders mainly uses liquid cooling, but it has the disadvantage of occupying a large space. Therefore, in the future, we will analyze and optimize the geometric structure of the retarder, type of coolant, and layout mode.

From this study, it can be concluded that there is still a way to achieve the popularization of retarders; on the one hand, it needs the support of national policies; on the other hand, it needs to improve the performance of retarders in all aspects. The advantages and disadvantages of the various retarders are complementary and integrated. Key technologies, such as thermal cooling, intelligent information technology, and energy recovery, are important solutions to these challenges. Liquid-cooled electromagnetic retarders have a wide range of prospective applications. Its high braking torque compensates for the fatal shortcoming of an ECR, and its remarkable low-speed braking ability compensates for the fatal shortcoming of the low-speed braking force failure of a HR. Liquid-cooled electromagnetic retarders are expected to play an important role in future markets.

REFERENCES

[1] E. Lin, "Effect of load weight on drum brake temperature field," *Metall. Equip.*, no. 6, pp. 48–51, 2021.

[2] C. Li, J. Jin, and L. Yang, "A comparative experimental study on thermal fade performance of disc and drum brakes," *Automot. Eng.*, vol. 39, no. 12, pp. 1397–1401 and 1430, 2017.

[3] D. Laze, G. Achimas, and I. T. Zelea, "Hydrodynamic retarder for commercial vehicles," *Acta Technica Napocensis Ser.-Appl. Math. Mech. Eng.*, vol. 59, no. 3, pp. 319–324, 2016.

[4] J. Bae, Y. Kim, Y. Son, H. Moon, C. Yoo, and J. Lee, "Self-excited induction generator as an auxiliary brake for heavy vehicles and its analog controller," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 3091–3100, May 2015.

[5] C. Liu, X. Zhang, and X. Song, "Electromagnetic field analysis for permanent magnet retarder by finite element method," in *Proc. Asia–Pacific Eng. Technol. Conf. (APETC)*, 2017, pp. 1–5.

[6] L. Kong, N. A. Wei, H. Mu, and Q. Yan, "Research on partially filled characteristics of vehicular hydrodynamic retarders," *Int. J. Heavy Vehicle Syst.*, vol. 27, no. 6, p. 817, 2020.

[7] C. Wu, M. Xu, H. Li, and L. Guo, "Vehicle characteristics analysis and the development trend of hydraulic retarder," *Vehicle Power Technol.*, no. 1, pp. 51–55, 2011, doi: 10.16599/j.carolcarrollnki.1009-4687.2011.01.010.

[8] Y. Chai, P. Zhang, and H. Chen, "An integrated hydraulic retarder regulating device," Chinese Patent CN 217 558 840 U, Jun. 22, 2022.

[9] L. Mu, X. Yang, and F. He, "A fixed-axle power shift transmission with a hydraulic retarder," Chinese Patent CN 217 440 644 U, Jun. 14, 2022.

[10] Y. Han, S. Li, and J. Song, "A high-power hydraulic speed retarder control method," Chinese Patent CN 114 919 553 A, May 25, 2022.

[11] F. Shi, J. Xu, and Z. Zhou, "A control method and device based on an ABS hydraulic retarder," Chinese Patent CN 114 919 550 A, May 6, 2022.

[12] Nippon Steel Corporation, "Eddy current retarder with electricity generating function," *Energy Ecol.*, 2020.

[13] Y. Chevalier, "Damping in materials and structures: An overview," in *Generalized Models and Non-classical Approaches in Complex Materials 2*. Springer, 2018, pp. 1–27.

[14] Nippon Steel Corporation, "Eddy current retarder," *J. Eng.*, 2020.

[15] P. K. Agyeman, G. Tan, F. J. Alex, D. Peng, J. Valiev, and J. Tang, "The study on thermal management of magnetorheological fluid retarder with thermoelectric cooling module," *Case Stud. Thermal Eng.*, vol. 28, Dec. 2021, Art. no. 101686.

[16] D. You, "Thermal management of water retarder for commercial vehicle," Jilin Univ., Changchun, China, Tech. Rep., 2015.

[17] Y. Lei, P. Song, and Y. Fu, "Design of constant-speed control method for water medium hydraulic retarders based on neural network PID," *Automot. Innov.*, vol. 3, no. 2, pp. 147–157, Jun. 2020.

[18] M. Chen, X. Guo, G. Tan, X. Pei, and W. Zhang, "Effects of blade lean angle on a hydraulic retarder," *Adv. Mech. Eng.*, vol. 8, no. 5, May 2016, Art. no. 168781401664805.

[19] S.-C. Jung, I.-S. Yoon, and J.-S. Ko, "Electromagnetic retarder's power recovery device and voltage control," *Trans. Korean Inst. Power Electron.*, vol. 21, no. 5, pp. 396–403, Oct. 2016.

[20] Z. Ding, X. Mei, and Y. Ni, "Automotive electric eddy current retarder control system," Chinese Patent CN 210 526 310 U, May 15, 2020.

[21] J. Tian, Z. Wang, and K. Ning, "An electric current retarder with tooth coil excitation," Chinese Patent CN 1146 29 326 A, Apr. 13, 2022.

[22] W. Zhang, S. Bian, and W. Dong, "An electric eddy current retarder," Chinese Patent CN 217 029 703 U, Mar. 4, 2022.

[23] Z. Ying, "A water-cooled self-excited electric vortex flow retarder," Chinese Patent CN 216 490 180 U, Dec. 14, 2021.

[24] W. Guo, D. Li, L. Ye, Z. Gao, and K. Zhang, "Performance analysis of a novel self-excited, liquid-cooled, and bridge integrated electromagnetic retarder for heavy vehicles with trailer," *Int. J. Automot. Technol.*, vol. 20, no. 5, pp. 1023–1032, Oct. 2019.

[25] K. Zhang et al., "Numerical simulation and experimental study of self-excited liquid-cooled electromagnetic retarder," *Automot. Eng.*, vol. 37, no. 6, pp. 699–706, 2015.

[26] Z. Ding, Z. Shen, X. Mei, M. Qu, and T. Hao, "Design of control system of electromagnetic liquid cooling retarder for automobile," *Electron. Compon.*, vol. 42, no. 6, pp. 1610–1616, 2019.

[27] J. Tian, D. Li, and L. Ye, "Study on braking characteristics of a novel eddy current-hydraulic hybrid retarder for heavy-duty vehicles," *IEEE Trans. Energy Convers.*, vol. 35, no. 3, pp. 1658–1666, Sep. 2020.

[28] Y. Liao, "Classification and characteristics of vehicle retarder," *World Sci. Res. J.*, vol. 5, no. 10, pp. 88–94, 2019.

[29] L. Ye, Y. Liu, and D. Li, "Performance analysis and optimization of liquid-cooled and flywheel-type eddy current retarder," *IEEE Trans. Magn.*, vol. 55, no. 6, pp. 1–5, Jun. 2019.

[30] D. Ferreira, T. Howell, and P. Jo, "Hydraulic lash adjuster compatible engine brake," *SAE Int. J. Engines*, vol. 9, no. 4, pp. 2286–2291, Sep. 2016.

[31] S. Liu, "Research on performance test system of electrotex current retarder," Zhejiang Univ., Zhejiang, China, Tech. Rep., 2004.

[32] Z. Gao, D. Li, J. Tian, K. Ning, and L. Ye, "Design and performance analysis of a novel radially distributed electromagnetic-hydraulic retarder for heavy vehicles," *IEEE Trans. Energy Convers.*, vol. 37, no. 2, pp. 892–900, Jun. 2022.

[33] J. Liu, "Research on heat dissipation system of electro eddy current retarder," Harbin Inst. Technol., Harbin, China, Tech. Rep., 2018.

[34] D. Li, W. Wang, and M. Li, "An eddy current air-cooled retarder with double salient pole structure," China Patent CN 2014 10 596 672, Oct. 29, 2014.

[35] Y. Lei, P. Song, H. Zheng, Y. Fu, Z. Liu, and X. Fu, "Constant speed control method of hydraulic retarder based on fuzzy PID," SAE Tech. Paper 2017-01-1113, 2017.

[36] Z. Ding, X. Mei, and Y. Ni, "Eddy current retarded trailer with anti-push-head function," Chinese Patent CN 110 562 045 B, Sep. 6, 2022.

[37] C. Liu, W. Bu, and T. Wang, "Numerical investigation on effects of thermophysical properties on fluid flow in hydraulic retarder," *Int. J. Heat Mass Transf.*, vol. 114, pp. 1146–1158, Nov. 2017.

[38] W. Liu, G. Tan, J. Li, X. Li, F. Mou, and Y. Ge, "Integrated cooling evaporation system for the hydraulic retarder," SAE Tech. Paper 2015-01-1612, 2015.

[39] Z. Yuan et al., "Based on the heat flow and solid coupling process of vane hydraulic retarder strength analysis," *J. Jilin Univ., Eng. Sci.*, vols. 46–48, no. 5, pp. 1506–1512, 2016, doi: 10.13229/j.carolcarrollnkijdxbgxb201605018.
[40] T. Wang, G. Tan, X. Guo, S. Xiong, Z. Zhang, and X. Gao, "Energy saving analysis of vehicle hydraulic retarder thermal management system based on Rankine cycle," SAE Tech. Paper 2016-01-1941, 2016.
[41] Y. Ji, J. Wang, Y. Xu, Z. Liu, Y. Zhou, and J. Li, "Study on the thermal-magnetic coupling characteristics of integrated eddy current retarder," SAE Tech. Paper 2016-01-0185, 2016.
[42] F. Yaojing, X. Xiangshuai, and H. Shoudao, "Design research of high power oil-cooled electrical eddy current retarder for heavy vehicles," in *Proc. 19th Int. Conf. Electr. Mach. Syst. (ICEMS)*, Nov. 2016, pp. 1–5.
[43] B. Jiao, "Multi-field coupling analysis and optimal design of electromagnetic liquid cooling retarder," Beijing Univ. Technol., Beijing, China, Tech. Rep., 2014.
[44] X. Li, L. Ye, M. Li, and Q. Lv, "Research on temperature and braking performance of water-cooled eddy current retarder," *IEEE Access*, vol. 9, pp. 38991–38998, 2021.
[45] J. Tian, D. Li, K. Ning, L. Ye, K. Zhang, and C. Hu, "The study of the air gap optimization for the liquid-cooled and embedded eddy current retarder considering thermal deformation," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Oct. 2019, pp. 1–5.
[46] J. Tian, D. Li, K. Ning, and L. Ye, "Research on heat dissipation optimization of a novel liquid-cooling eddy current brake," *IEEE Trans. Energy Convers.*, vol. 36, no. 1, pp. 131–138, Mar. 2021.
[47] Z. Gao, D. Li, and B. Guo, "An accurate magnetic-thermal coupling model for thermal decay analysis of eddy current brakes," in *Proc. IEEE 2nd China Int. Youth Conf. Electr. Eng. (CIYCEE)*, Dec. 2021, pp. 1–6.
[48] L. Chengye, J. Kejun, and Z. Yan, "Study on temperature rise performance of eddy current retarder in automobile," in *Proc. Int. Conf. Future Inf. Technol. Manage. Eng.*, Oct. 2010, pp. 550–553.
[49] B. Mei, X. Guo, G. Tan, M. Chen, B. Huang, and L. Xiao, "Study on commercial vehicle ECR thermal management system," SAE Tech. Paper 2016-01-1935, 2016.
[50] W. Song, S. Wang, S.-B. Choi, N. Wang, and S. Xiu, "Thermal and tribological characteristics of a disc-type magnetorheological brake operated by the shear mode," *J. Intell. Mater. Syst. Struct.*, vol. 30, no. 5, pp. 722–733, Mar. 2019.
[51] H. Zhao, B. Wang, and G. Chen, "Numerical study on a rotational hydraulic damper with variable damping coefficient," *Sci. Rep.*, vol. 11, no. 1, p. 22515, Nov. 2021.
[52] J. Li, G. Tan, Y. Ji, Y. Zhou, Z. Liu, and Y. Xu, "Design and simulation analysis for an integrated energy-recuperation retarder," SAE Tech. Paper 2016-01-0458, 2016.
[53] X. Sun, L. Ling, S. Liao, Y. Chu, S. Fan, and Y. Mo, "A thermoelectric cooler coupled with a gravity-assisted heat pipe: An analysis from heat pipe perspective," *Energy Convers. Manage.*, vol. 155, pp. 230–242, Jan. 2018.

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