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Research Paper

3D investigation into the thermal behavior of the wet multi-disk axle brake of an off-highway machinery

Samrendra K. Singh, Hesam Abbassi *, Panos Tamamidis

CNH Industrial, Burr Ridge, IL 60527, United States

HIGHLIGHTS

- A framework to model the fluid flow and heat transfer in an axle housing is proposed.
- Fluid flow and heat transfer inside the housing divided into two separate sub-models.
- Heat transfer coefficient derived from the fluid model mapped onto the wetted solids.
- Transient heat transfer modeled and correlated with test over multiple braking cycle.

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ABSTRACT

Accurate prediction of the thermal behavior of the axle-brake systems is an imperative part of the design process of the braking systems in off-highway machinery. The frictional heat generated during repetitive braking cycles under heavy braking loads can cause several negative effects including brake fade, thermal cracks and even fluid vaporization. Despite its significance, limited capability has been developed to predict the thermo-fluids of the wet axle-brake systems. The multi-scale and multi-physics nature of the problem in combination with the significant complexity of the geometries involved renders the application of the common-practice computational fluid dynamics (CFD) methods impractical. This paper, proposes a framework for the application of CFD to predict the time-dependent thermo-fluid state of a wet axle-brake system under repetitive braking with varying loads. The thermal model includes full consideration of the heat transfer in the friction pairs, air-oil mixture, and eventually the surrounding solid parts. To achieve this goal, the problem is broken into two sub-problems: the flow between a pair of the friction and separator plates, the global solution of the fluid motion of the air-oil mixture in the housing and eventually the heat transfer in the solid parts. Finally, the temporal evolution of the temperature in both fluid and solid phases predicted by the proposed simulation method, are validated against experimental measurements showing good correlation level.

1. Introduction

Deceleration of a moving vehicle usually involves the use of a braking system where the kinetic energy is converted into frictional heat. Among many diverse types of braking systems, multi-disk oil-cooled brakes have been gaining popularity in the past decades. These types of brakes are widely used in construction equipment and other heavy duty off-highway vehicles and are well suited for prolonged braking intervals leading to an enormous amount of heat generation in the system. Use of a conventional dry brake system would lead to unacceptable high temperature and thermal stresses in the brake parts and thus making their use impractical. Unlike the conventional dry brakes, the friction pairs in wet brakes operate under fluid lubrication. Because of the provided lubrication, the mechanical and thermal loading on the mating parts reduces, increasing the life of the oil cooled friction units compared to dry brakes. On the contrary, the frictional moment between the disks diminishes because of the lubrication film and to counter that effect, the use of a package with multiple friction plates and separator plates is necessary to ensure an adequate frictional force (Fig. 1). To provide better oil circulation and improve the cooling of the friction surfaces, the brakes are equipped with grooves. Forced oil motion between the mating friction parts allows for intensive removal of heat which will be transferred to adjoining components and eventually dissipated by convection cooling from the solid parts of the brake assembly. Each braking cycle consists of two phases, engagement and cooling.

* Corresponding author.
E-mail address: hessam.abbassi@gmail.com (H. Abbassi).

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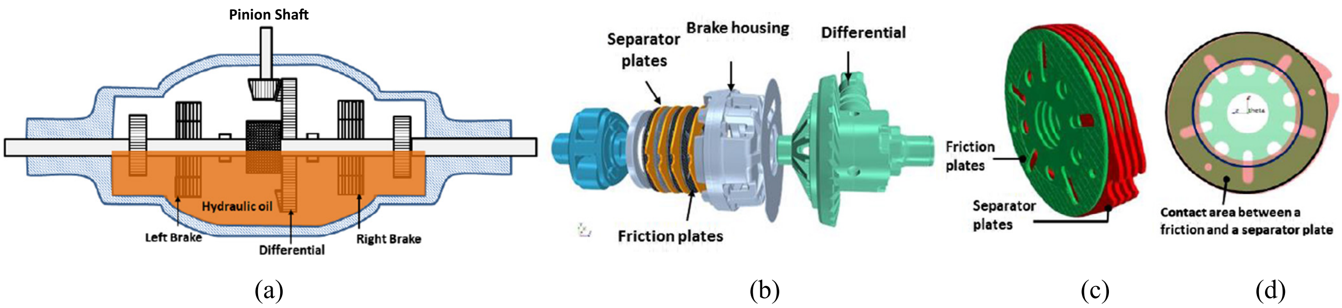

Fig. 1. (a) Schematics of an axle housing (b) Differential system, clutch type brake and final drive, (c) friction plates (green) and separator plates (red) (d) contact area between friction and separator plate during brake engagement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

During the engagement phase, a piston exerts force on the disks in axial direction squeezing the separator and friction plates together. The friction plates are coated with high frictional material e.g. paper or ceramic which gives rise to high frictional contact during the engagement phase and hence, resistance to the motion of the vehicle while converting the kinetic energy into heat. During the cooling phase, the brake disks are separated from each other and the hydraulic oil flows between them, which cools the plates while transferring the generated heat to the fluid.

It is important to be able to predict the thermal behavior of such system with precision, including the global temperature of oil in the housing, the temperature fluctuations in the contact zone as well as the solid parts. Excessive temperature rise in the lubrication oil can shorten its life and may even cause fluid vaporization. Similarly, elevated temperature and temperature gradients in the friction components can lead to many negative effects including the rupture of the lubricating film, premature wear, unacceptable thermal deformation of the disks, and even seizure of the unit. To better understand the significance of a properly designed braking system in off-highway machineries we should note that, they are typically move at slow velocities thus limiting the amount of airflow around the axle which is insufficient to facilitate rapid heat removal to ambient by convection or radiation. In addition, the air temperature around the axle is usually high due, in large part, to the heat from the engine cooling fan which inhibits any significant heat removal. Therefore, majority of the heat generated during braking application is absorbed by the axle raising its temperature during repetitive braking.

To simulate such a system in a holistic fashion, one needs to come up with a strategy to overcome the complexity of a problem incorporating many different phenomena at different time and length scales. The thermo-hydrodynamics of the flow in the contact zone is characterized by micro level length scales and shorter time scales while the fluid flow in the brake housing is at a macro-scale and the heat transfer in the solid parts pose a longer time scale to the problem. As a result of the importance of the thermal characteristics of the friction zone, many researchers focused on the micro-scale phenomena between the friction and the separator plates. Majority of these studies are aimed at developing capabilities to predict the temperature rise in the plates, which is the main cause of failure in wet brakes and clutches. These studies have utilized many different approaches ranging from mathematical and empirical models [1–6] to the advanced CFD methods for the calculation of heat transfer coefficients in the fluid film with varying degrees of simplifying assumptions [7–11]. Although, these studies are helpful in predicting the thermal behavior of the friction surfaces at a micro-level, they do not provide any insight into the "macro" scale or "global" thermal characteristics of the brake or clutch housing. To the authors' best knowledge there has not been any effort to model the thermo-hydrodynamics of a full wet brake system, however, there have been similar studies on geared systems. Most of these studies are based on the thermal extension of the elastohydrodynamic lubrication theory or TEHL [12–15]. The theory requires a simplification of the large-scale thermal-fluid phenomena inside the gearbox to decouple the large scale physics from the gears contact region [16–18]. Another simplification, allows for representing the fluid by some heat transfer coefficient approximation while solving the transient heat-conduction in the solid [19–22].

Despite the rather extensive amount of research in the area of multi-disk brake/clutch micro-scale modeling as well as macro-scale fluid-mechanics simulations in the geared systems and gearbox solid housings, the interaction of the two has not been a subject of investigation due, in large part, to the immense separation of length and time-scales that exists between the two phenomena. This paper aims to propose a modeling strategy to study the interaction of various thermo-fluid phenomena within a full wet brake housing from the friction plate to the solid housing. The problem is broken down into two subproblems; the convective heat transfer from the air-oil mixture in the housing to the solids and the heat conduction in the solid parts. This modeling approach enables us to investigate the temporal and spatial evolution of the thermo-fluid phenomena and accurately predict the global system response during long braking cycles, using reasonable computational resources.

The paper is structured as follows: Sections 2.1–2.3 describes the problem and devises a solution strategy based on an illustration of the separation of physical length-scales and time-scales associated with various thermo-fluid physics within the system. We will present the governing equations as well as the modeling techniques in Sections 2.4 and 2.5, respectively. Section 3 formulates the numerical settings used to solve the governing equations and the specifics of the implemented schemes to weave different components of the solution into one. Section 4 describes the experimental setup, assumptions and data acquisition. Section 5 is reserved for presenting the simulation results as well as their validation against experimentally collected data for temperatures in the oil and solid components.

2. Model formulation

The brake system illustrated in Fig. 1 consists of two gears, generating motion in the oil which lubricates the multi-disk brakes. The kinetic energy of the vehicle is converted to frictional heat inside the brake friction pairs, and is then absorbed by the churning oil-air mixture inside the housing, which is primarily driven by the rotary motion of the internal parts. The oil acts as a transportation vehicle for the generated heat from its source to the other solids by convective heat transfer. By looking at the system from