

Experimental and CFD Analysis of Tire Cooling Sidewall

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ABSTRACT

Tire durability can be guided by fracture mechanics, where stress and temperature state in rubber play a key role. The temperature influences the fatigue metrics, such as crack propagation speed, with a significant nonlinearity, therefore temperature reduction in the visco-elastic media is known to be effective in enhancing the product life.

This paper introduces a new method to reduce the temperature by increasing the heat transfer across tire sidewall surface.

INTRODUCTION

The role of pneumatic tire in future car society is to provide safety, eco-friendliness and comfort. Especially, the public concern on global environment increases recently, which requires the development of environment-proactive tire. From the viewpoint of resource and energy saving, lightweight and low-fuel consumption tires are desired. More specifically, providing ample service life with least material is sought.

Most abundantly-used material in tire is rubber. So tire durability is dependent on fracture mechanics in rubber, where stress and temperature state play an important role. Rubber is originally characterized as the visco-elasticity, which is schematically shown in Figure 1. When cyclically-loaded due to rolling, the medium generates heat through hysteresis loss. If the heat in tire builds up excessively under certain service condition, the structure fails by crack propagation in rubber. Fig. 2 shows the interactive cycle between tire deformation and material property change. Most striking example is the run-flat tire, which can eliminate spare tire in trunk room if successful. As shown in Fig. 3, the tire has a pair of stiffened sidewall, which enables traveling 80km distance at 80km/h even if the tire is punctured. Since the sidewall deflection of punctured run-flat tire is almost twice as large as un-deflated level, the heat generation under that condition is extraordinarily large. In some cases, inside temperature of sidewall reaches 200 degrees Celsius at the last second of failure.

To overcome this situation, the method has generally been taken to reduce tire deformation by stiffening sidewall. However, significant disadvantages are observed from environment and comfort viewpoints: additional reinforcement to the sidewall, increased transmissibility from road excitation to spindle force.

Knowledge on fracture mechanics of rubber indicates that even a reduction of temperature contributes largely to fatigue life extension under certain condition because crack propagation law has a significant nonlinearity of temperature as compared with stress. For this reason, we seek finding a new method to reduce tire temperature.

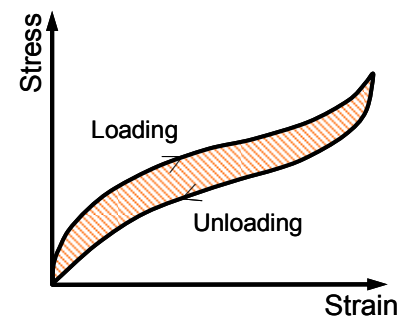


Fig. 1: Visco-elastic character of rubber.

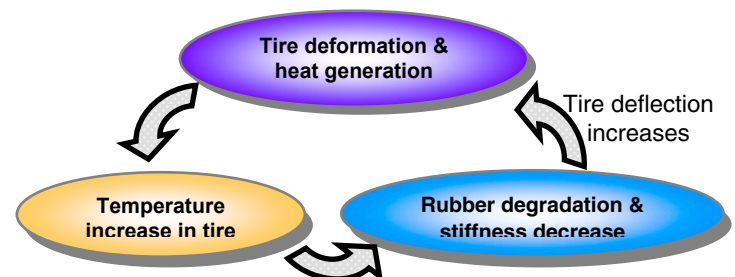


Fig. 2: Cyclic interaction between tire deformation and temperature.

THE METHOD OF TIRE COOLING

Concept

Important factors to be considered in thermal design of tire are that:

- rubber plays roles of both heat generator and radiator,
- rubber has a low heat conduction.

With these characteristics in mind, we look into physics Fig. 4 describes schematically the heat flow across tire sidewall with energy dissipation by aerodynamics. Note that tire sidewall is not perfectly smooth because of the presence of alphabet and numeric letters. The heat flow originates mainly from the reinforcement rubber, where large deformation in punctured condition generates continuously heat through hysteresis behavior of rubber. Fig. 5 shows the concentration of principal strain in the reinforcement rubber, hence heat source and failure point. If it is succeeded to cool off effectively the sidewall surface corresponding to the failing area, temperature reduction inside the sidewall and then durability enhancement can be expected. This is because the direction of heat flux at the sidewall is mainly from tire inside to outside.

Preliminary experiment was conducted to be tipped for cooling method, and we decided to control actively the air flow on the sidewall. As shown in Fig. 4, deploying protrusions of optimum geometry could increase heat transfer across the sidewall surface. Another important fact found in the experiment is that enlarging surface area for heat radiation does not reduce surface temperature because heat conduction of rubber material is extremely low in comparison with metal.

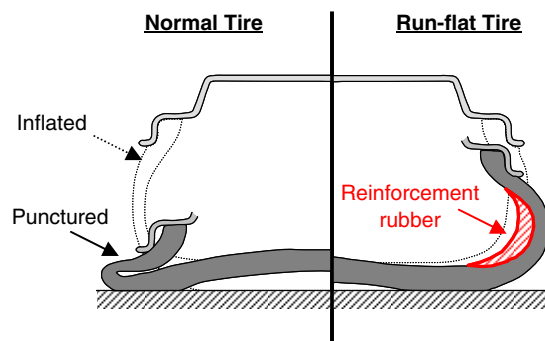


Fig. 3: The run-flat tire.

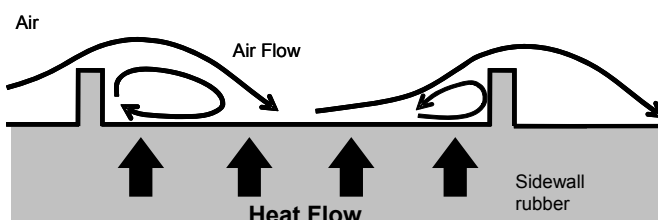


Fig. 4: The concept of tire sidewall cooling.

Air flow pattern influencing the heat transfer

To find efficient flow parameter for surface temperature reduction, a series of experiments and CFD analyses were conducted. In fact, literature written on heat transfer of polymeric rotating system such as tire is very few. As a first step, unidirectional flow over rubber plate and protrusion is considered to investigate fundamental property of heat transfer.

The experimental setup is shown in Fig. 6. Film heater (made of silicon rubber, O&M Heater Co.) is placed on plate rubber and heat flux generation is kept constant. Air blower generates approximately a unidirectional flow with the wind velocity of 50km/h which is measured by the wind mill anemometer, CW-50 CUSTOM Co.. Rectangular protrusions of various dimensions are placed on the heater and the surface temperature is measured by infrared thermometer (CEDIP Co. JADEIII LWIR). Fig. 7 typically shows the temperature measured. Then, heat transfer coefficient can be calculated by equation (1) below, where $\alpha[W/(m^2.K)]$ is heat transfer coefficient, $q[W/m^2]$ is heat flux measuring by heat flux sensor (Kyoto Electronics Manufacturing Co.), T_{wall} is heater surface temperature, and T_{air} is reference temperature of air. In calculating α , projected area of protrusions is eliminated because the temperature on bottom surface is of main interest.

$$\alpha = \frac{q}{T_{wall} - T_{air}} \quad (1)$$

After averaging over the surface of interest, we summarize the effect of disturbed flow by equation (2). This is done by the comparison with α_{plate} , the heat transfer coefficient without any protrusions. Typical value of α_{plate} is 61.5 W/(m²K).

$$\alpha_{eva} = \frac{\alpha}{\alpha_{plate}} \quad (2)$$

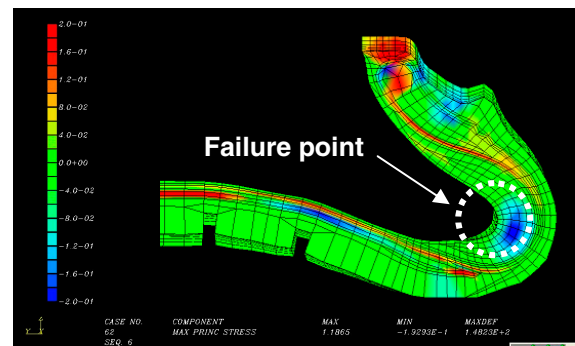


Fig. 5: Principal strain distribution of run-flat tire.

Fig. 8 shows the definition of related parameters: protrusion dimensions, pitch length, a parameter of temperature distribution. The width of protrusion, w , is kept constant through the experiment.

It was found in Fig. 9 that $x_{\min}$, minimum temperature position between protrusions, normalized by h , protrusion height is plotted like a plateau regardless of the variation in p/h . This suggests that $x_{\min}$ nearly depends on h and that air flow around the obstacle is related.

Fig.10 indicates that:

- optimum p/h exists for achieving maximum heat transfer coefficient α_{eva} ,
- the influence of w on α_{eva} is very small.

Note again that in calculating α_{eva} the projected area of protrusion is eliminated. Therefore the performance of small p/h is overestimated in real heat transfer; protrusion area on bottom surface has high temperature. Fig. 10 also shows that when h is 4mm, α_{eva} is smaller than other h . The reason is that α_{eva} varies from point to point: maximum α_{eva} stays at the same level but minimum α_{eva} is smaller at different point.

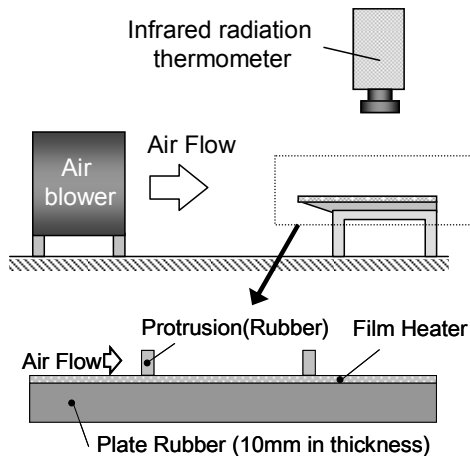


Fig. 6: The setup of one-directional flow experiment.

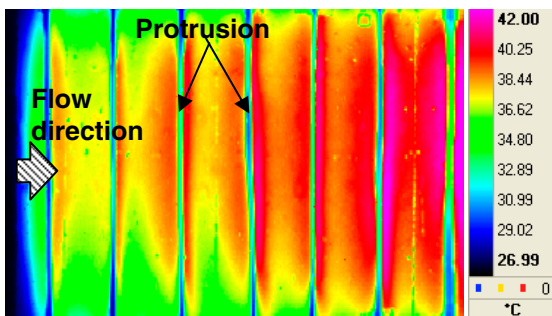


Fig. 7: Temperature distribution (measured).

To visually distinguish air flow pattern which clearly affects the heat transfer coefficient, CFD analysis is performed by using the identical geometry with the experiment. Large Eddy Simulation⁽¹⁾ method is adopted. Typical FE model used is shown in Fig. 11.

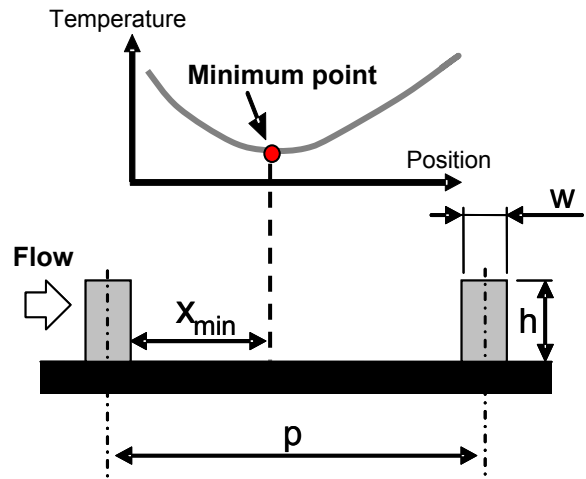


Fig. 8: Parameter definition.

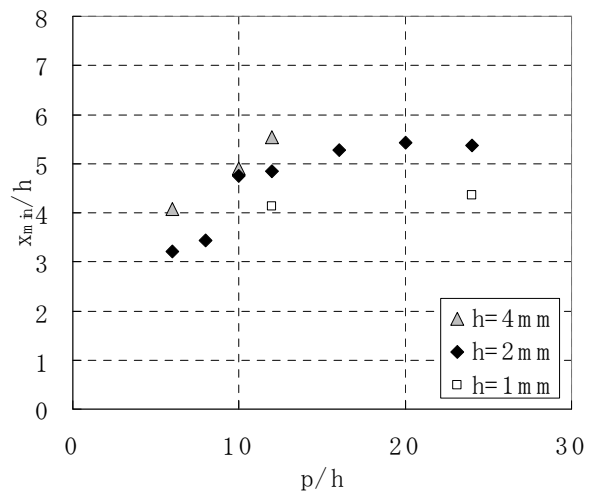


Fig. 9: Relation between $x_{\min}/h$ and p/h .

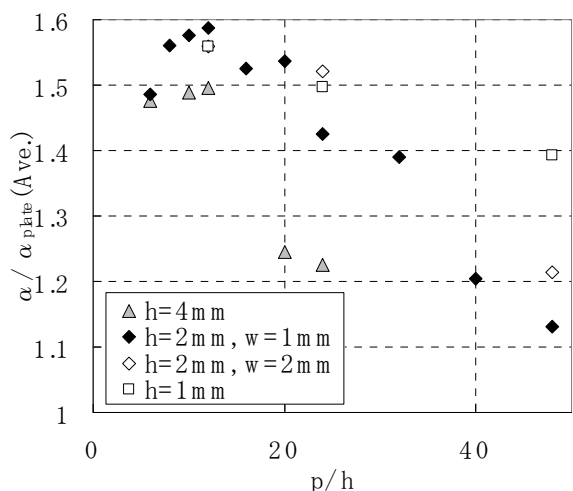


Fig. 10: Relation between $\alpha/\alpha_{\text{plate}}$ and p/h .