Recent Patents On Engineering **2 (2008) pp. 87-94** *Netscher et al.*

A Review of Patents in Tyre Cooling

N.W. Netscher[1], S.M. Aminossadati[1] and K. Hooman[2*]

[1]CRCMining, School of Engineering, The University of Queensland, QLD 4072, Australia
[2*] School of Engineering, The University of Queensland, QLD 4072, Australia (correspondent author)

ABSTRACT

A number of patents on tyre cooling have been reviewed with a focus on those which can be applied to earthmoving tyres for the mining industry. The mechanisms of heat transfer within the tyre carcass are introduced as well as the basic tyre structure and effects of overheating on tyre operation. The tyre cooling patents are separated into five functional groups and reviews are made based on practicality and potential for significant heat transfer. This analysis has made it evident that potential cooling effectiveness is often compromised by practicality of an invention. The patents deemed to have the most potential for cooling are those which incorporate a working fluid which undergoes a phase change to transfer heat between different regions of the wheel assembly. Finally, these inventions are also related to current research projects which aim to develop a new cooling technique and extend the working life of earthmoving tyres.

Keywords: tyre cooling, heat dissipation, rotating heat pipes, air circulation, conduction heat transfer, tyre chamber

1. Introduction

1.1. Significance to Industry

The generation of heat within earthmoving tyres plays an important part in the operation of many mining companies. For some operations, the non control over this undesirable heat generation leads to premature tyre failure due to heat separation while other operations who manage tyre temperature generation suffer extensive production losses due to premature park-up of equipment.

The control of tyre temperature or TKPH (Industry standard for tyres - Tonnes per Kilometre per Hour) has traditionally occurred through management of truck TKPH. Tyre manufacturers have played an important part in developing new compounds which are more heat resistant in nature. Despite the management of tyre temperature (TKPH), efficient maintenance, monitoring strategies and developments in tyre technology, sites continue to suffer from premature failures and production losses due to extreme overheating risks. Implementing an efficient cooling strategy will result in reducing the thermal stresses to the tyre and extending the tyre life. This has been important due to the ever increasing efficiency of modern mining operations with high speed equipment and reduced waiting times within all areas of the operation.

This paper will review a number of patents relating to tyre cooling, with the application of mining haul trucks in mind. With such trucks heat management has been a constant issue for tyre manufacturers and consumers for decades. Tyre operating limits are the main limiting factor in mine production, forcing trucks to carry restricted loads and travel at lower than necessary speeds. Hence, there is a definite need for an effective and active method for heat dissipation in earthmoving tyres. This problem is not only of interest in the mining industry and those dealing with heavy and high speed machines but also is of fundamental scientific significance. This review paper is designed to address this important issue.

1.2. Tyre Structure

Earthmoving pneumatic tyres have a number of structural layers within the carcass. These are included primarily for strength and wear resistance purposes. Fig. (1) illustrates some of the major earthmoving tyre sections and components, sourced from a Bridgestone safety manual [1]. Although the tyre carcass can withstand high loads and has reasonable wear properties, it has very low thermal conductivity and therefore cannot effectively dissipate the heat to the surrounding atmosphere. Before moving to elaborate on the details, it is important to briefly introduce the mechanisms and nature of the heat generation within the carcass.

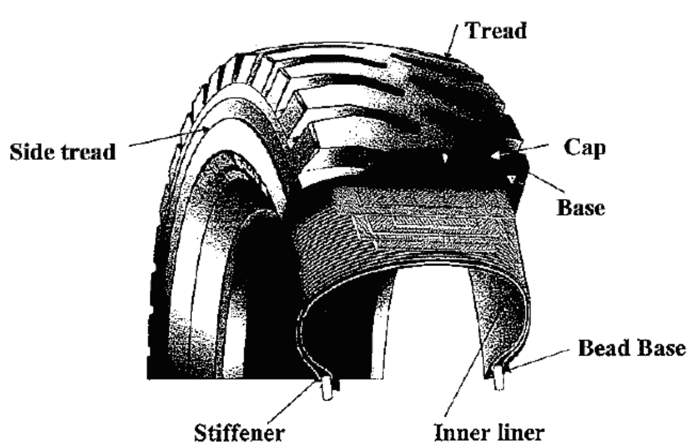

Fig. (1): Structural Components in Earthmoving Tyre [1]

1.3 Heat Generation

To estimate the exact heat generation rate in tyres, it is required to fully understand the structure and rolling and flexing mechanisms of tyres. The fundamental phenomenon behind the heat generation in tyres is the friction between molecules when the rubber in the structure of the tyre is under a kinematic deformation by a continuous compression-tension or torsion [2]. This kinematic deformation is known as the hysteresis effect. In fact, as the tyre rolls and flexes, a portion of the motive power transmitted to the tyre is absorbed due to the tyre hysteresis and thus converted into heat and consequently the tyre temperature increases [3, 4]. This effect is aggravated by increased load and speed as well as tyre under-inflation, road undulations and excessive cornering. Tyre hysteresis which accounts for much of the increase in temperature is an unsteady effect – causing heat to be generated by different amounts in different sections of the tyre carcass [3] making it quite complex to model. However, Kainradl and Kaufmann [3] presented a simplified formulation to determine the heat generation in tyres. In their formulation, the heat generation is calculated based on the energy loss per cycle of a volume unit which undergoes a sinusoidal deformation. Accordingly, the heat generated per unit time is

$$Q = H f / J , \tag{1}$$

wherein f is the frequency in Hz (s^{-1}), $1/J$ is estimated as 2.343 $Cal/(mKg_f)$ and H is the deformation amplitude given by

$$H \approx \sigma_a \varepsilon \ \tan \delta , \tag{2}$$

in which σ_a is the stress amplitude, ε is the sinusoidal deformation amplitude and δ is the phase angle between stress and deformation.

Heat is also generated within the tyre carcass due to the friction at the tyre-road interface. The friction force depends on the nature of the surface roughness and the sliding velocity [5-8]. Literature also indicates a number of other experimental and theoretical studies, which investigate the heat generation phenomenon in tyres. These outline results which are important to any prospective tyre cooling technique. Some of the experimental studies looked at the effects of operating conditions on the tyre thermal behaviour and showed that the vehicle load has the most pronounced effect on tyre temperature in comparison to speed, inflation pressure and slip angle [9]. Other studies examined the temperature distributions in the tyres for various structures, materials and thermal characteristics of the tyre [10-14].

As a result of the poor thermal conductivity of rubber, the temperature rise is primarily dependent on the thickness of tread [15]. If the heat generation is faster than it can be transferred into the ambient air, it gradually builds up in the tyre and reaches its maximum at the outermost ply or belt (see Fig. (**2**)). As the operating temperature of the tyre increases the rubber considerably loses its strength. The tyre becomes more vulnerable to malfunction from fatigue, impact, cut and heat separation. Tyre operating temperature is shown to have a significant impact on tyre life in Fig. (**3**) [17]. If the tyre carcass is maintained at low temperatures then its life can be considerably extended.

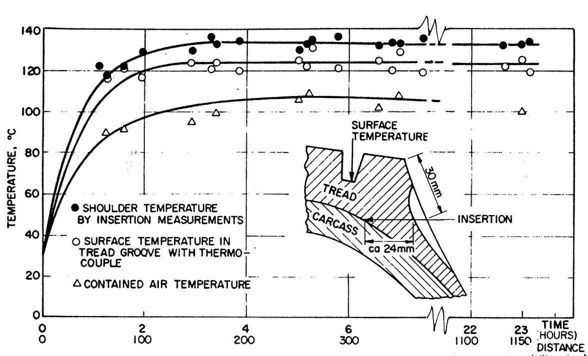

Fig. (2): Tread and shoulder temperature for a truck tyre [16]

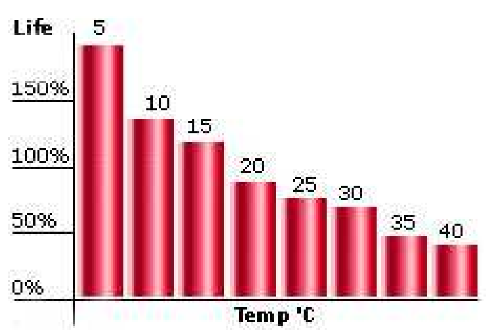

Fig. (3): Effects of temperature on tyre life [17]

Heat build-up can affect tyres in a number of ways. Fig. (4) shows several forms of tyre damage and their location on the tyre carcass for a bias type tyre. With increased temperature, the properties of rubber change so tyres become more susceptible to these types of mechanical failures [18]. In addition, the pressure within the tyre increases with temperature, linearly to the first approximation, as the ideal gas assumption suggests, and this, in turn, reduces the safety of the tyre. Finally, oxidative degradation is accelerated at high temperatures as noted by [19].

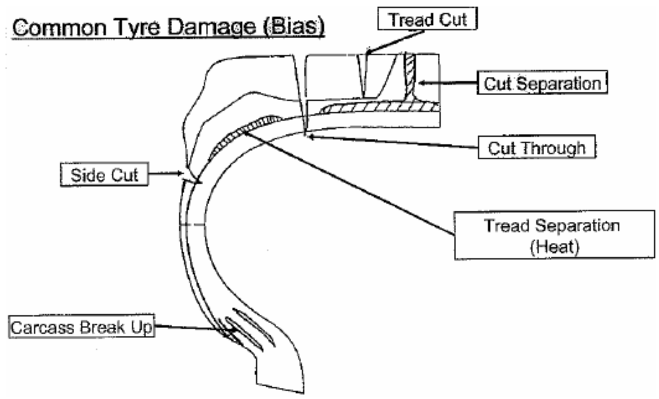

Fig. (4): Common Tyre Damage [19]

2. Tyre Heat Management

So far, there has not been any successful method of actively preventing haulage truck tyres from overheating while in use. Currently mine sites are limited to passive techniques in managing their haul truck fleet either through monitoring live TKPH levels in each truck tyre or through periodic temperature and pressure measurements. Unfortunately, these methods often have poor correlation to the actual state of the tyres and can be extremely conservative - thus leading to unnecessary losses in production. If an effective cooling method were implemented on mine sites, vehicle and tyre operation would be enhanced in a number of ways ultimately leading to increased site production. Even a drop of 5ºC could expand the operation of haul trucks, reduce rubber wear rates in tyres and improve tyre resistance to physical and chemical damage.

A number of cooling techniques have been identified through this patent review. As the materials used in wheel assemblies are such good thermal insulators, new methods of transporting heat to the environment are required to prevent rubber deterioration. These cooling techniques are categorised into five groups and their effectiveness and practicality will be discussed: 1.Conduction, 2.Forced Convection, 3.Refrigerant, 4.Tyre Carcass Modifications, and 5.Heat Pipe/Working Fluid. In what follows, we will review these techniques in detail.

2.1. Conduction

Inventions in this functional group suggest improving heat transfer by introducing improved conduction into the tyre chamber [20-25]. Several patents are briefly described below with comments on their operation and heat transfer feasibility. Gollert [20] proposed installing a number of metallic brushes inside the tyre chamber, which connect the rim and tread sections of the wheel assembly, as depicted in Fig. (**5**). As metallic conductors are much higher in thermal conductivity than the tyre carcass, it was claimed that sufficient and continuous heat transfer can be achieved. Furthermore, a liquid can be injected into the tyre chamber to interact with the rubber tyre and metallic brushes to aid in heat transfer. Groezinger [21] suggested incorporating a fluid transfer element which drapes over the rim and down into a pool of heat transferring fluid which collects at the bottom of the tyre chamber (Fig. (**6**)). The main advantage is that a cooling circuit which contains a secondary working fluid is also to be coiled around the rim in order to transport the thermal energy away from the wheel assembly. The fluid transfer element is driven by friction, absorbs some of the pooled working fluid, and transports it to the cooler rim for heat dissipation. Conceptually, it appears sound and should work fine; however, there might be a number of practical and operational issues which may not be immediately apparent. For example, a given molecule of working fluid is only in contact with the cooling coils at the rim for a short time, limiting the time for effective heat transfer. Moreover, the transfer element needs to remain in a stable, downward position at all times, which may not occur at variable speeds.

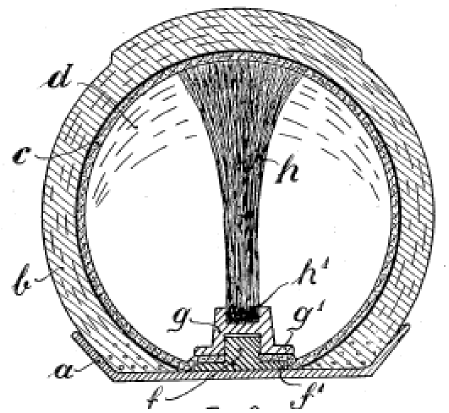

Fig. (5): Metallic brushes inside the tyre chamber [20]

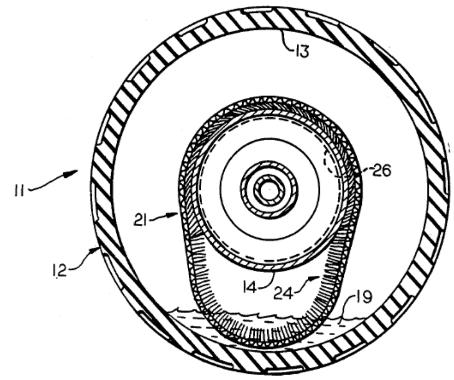

Fig. (6): Fluid Transfer Element inside Tyre Chamber [21]

Mote [22] proposed attaching a metallic ribbon to the inside tread surface of the tyre carcass (Fig. (**7**)) similar to a claim made by Gollert [20]. Two ends of the ribbon are to cross the tyre chamber, come into contact with the rim and partially stick out into the ambient air. The inventor claims, based on successful experimental results, that the metallic addition improves the overall heat transfer coefficient. The ribbon can be glued or tacked to the tread surface and requires a nylon cord for strength purposes. To prevent leakage from the tyre chamber, the end pieces need to be coated in a rubber-like material. Isham [23] claimed that having the tyre subject to heating with side walls relatively less subject to heating, a closed–filled resilient-walled conduit incorporated in part within the tyre would receive the heat and dissipate it away from the tread (Fig. (**8**)). This patent had many deficits such as the tyre balance issues, the appropriate coolant fluid, unknown range of temperature reduction, and technical issues with manufacturing and assembly.

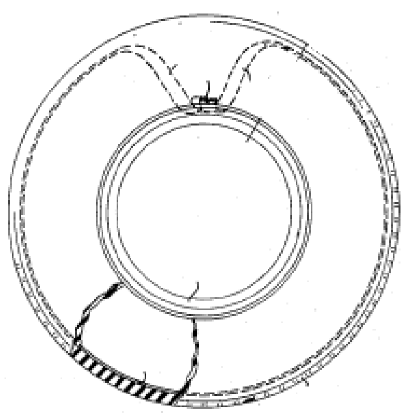

Fig. (7): Metallic ribbon to inside surface [22]

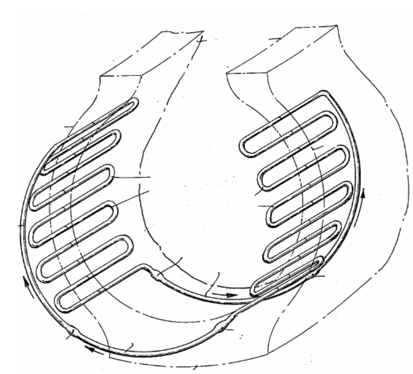

Fig. (8): Closed–filled resilient-walled conduit [23]

Although simple in principal, these patents all require structural changes to be made within the tyre and appear to provide limited heat transfer enhancement. There are no phase changes of the working fluids and the metallic contacts operate on a restricted surface area. Furthermore, these inventions usually require heat to be transferred to the surrounding atmosphere as opposed to a refrigeration unit and so there may not be a significant driving force for heat dissipation. On the whole there is no mention of corrosion protection of the metallic elements or whether the fluid or metal will interact with the rubber composite material.

2.2. Forced Convection

A number of patents were identified in this functional group. These either create forced convection within the tyre chamber or across the outside of the tyre carcass in order to enhance the heat dissipation rate. Several of these are discussed briefly below in relation to the methods proposed, potential heat transfer, and practicality.

A series of patents submitted by Skidmore [26-28] outlined the possibility of improving the heat transfer rate by increasing gas circulation within the tyre chamber. The circulating air within the chamber creates forced convection and thus, hence improves the heat transfer between the hot tread sections, the cooler sidewall, and the rim regions. One embodiment of the inventions is to use a number of raised spiral ribs on the inside surface of the tread extending up to two inches inward. Another proposal of the inventor is to attach a perforated flexible tube to either the inside of the tread section (see Fig. (**9**)) or the outside of the rim of the tyre assembly which compress and expand as the wheel rotates. This creates a bellows-type effect which will cause the outer tube to puff hot air inward toward the rim and sidewalls while the inner tube will create puffs of cooler air back to the tread sections. It is claimed that by changing to an inflating fluid of higher density the heat transfer processes will be more effective. Some apparent drawbacks for this invention include;

- The heat sink in this cooling technique is a combination of the tyre sidewalls and rim. However in mining applications, these regions also reach reasonably high temperatures. Therefore, the temperature gradient across the tyre would not be that steep and so there would be minimal driving force for heat transfer.
- The described 'bellows' technique for circulating the air within the tyre chamber may work adequately in a smaller car tyre. However, in haul trucks the thickness of the tread is substantially high which may diminish any flexing of the perforated inner tubing.

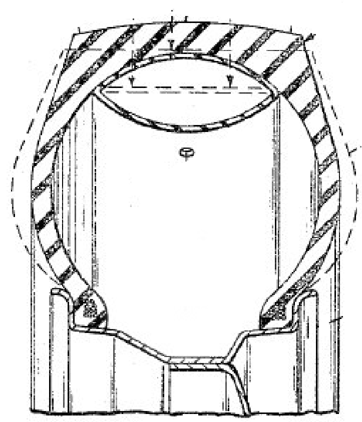

Fig. (9): Detailed view showing perforated outer tube within chamber [26]

Other inventions propose installing air ducts to direct more flow across the tyre carcass to increase the heat transfer coefficient for forced convection [29-32]. Weisbarth et al. [33] designed a front cover for a passenger vehicle to direct air over the tyres thereby improving cooling as well as aerodynamic flow particularly at the front wheels (Fig. (**10**)). Furthermore, Becker [34] proposed an air duct which funnels ambient air into the face of an air fender or rotating tyre. The duct contains a number of baffles as seen in Fig. (**11**) and has been designed with truck-trailers in mind. These claims may not be as applicable in the mining industry as the trucks may not be travelling fast enough for the additional air to affect the heat transfer rates appreciably. Also the added structures to the truck body may not be able to withstand any collisions or the general operation of haulage trucks.

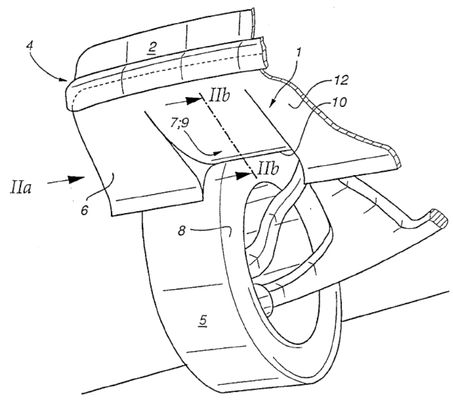

Fig. (10): Front cover to direct air [33]

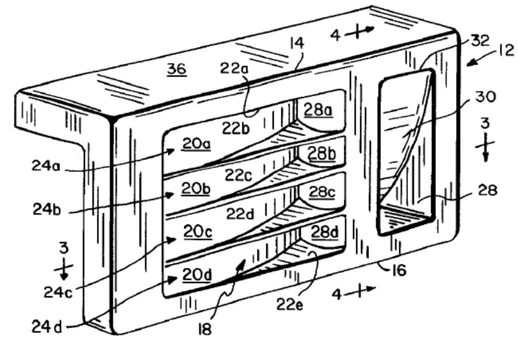

Fig. (11): Air Duct for Cooling Rotating Tyres [34]

2.3. Refrigerant Type Patents

These patents use a refrigeration circuit to draw heat away from the tyre carcass and dissipate it, usually through a separate cooling unit located on the car body [35, 36]. A two-stage cooling system is suggested by Hart [37] in which a primary heat transfer fluid is positioned within the tyre cavity and a secondary cooling circuit is coiled around the tyre rim. A basic schematic is shown below in Fig. (12) with numbered components.

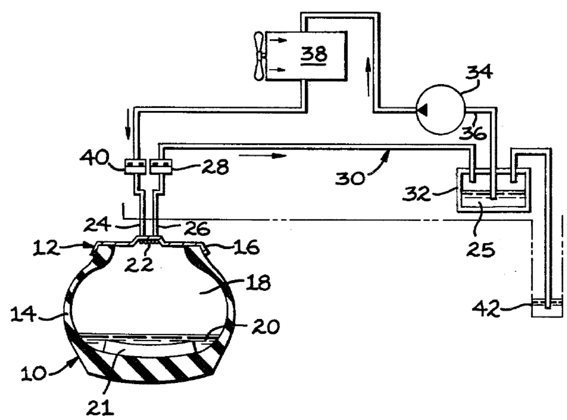

Fig. (12): Schematic of Cooling System [37]

The primary working fluid (20), quoted as a liquid, is contained within the tyre chamber and absorbs the heat from the rubber tread as the tyre is rotating. The centrifugal force should be sufficient to force the fluid to travel up the circumference of the tyre and subsequently fall onto the cooler rim and coils. Paddles (21) are also suggested to extend inwards to ensure that the liquid flows over the rim in lower velocity applications.

The secondary circuit coils around the tyre rim and, thus, is in direct contact with any working fluid or heat transfer medium within the tyre chamber. The circuit would contain a heat exchanger (38), fluid reservoir (32) and pump (34). The connection between the rotating tyre and truck is to be made with wheel seals (40, 28) which includes a sump for collecting leakage which may be common with the final drive sump (42). It is suggested that this secondary fluid is the same as that used for the final drive which eliminates problems such as contamination and segregation. As the cooling circuit is isolated (pressure-wise) from the tyre chamber, it can be at near to atmospheric pressure, significantly reducing potential leaks. The heat exchanger (38) may be an air cooled radiator or a refrigerated loop heat exchanger (i.e. a third fluid would be required). All four wheels may be connected in parallel to the one pump circuit.

The heat transfer process has been enhanced as the tyre is no longer relying on convection to the surrounding air as a method of heat dissipation. If a strong conducting fluid is used then the heat should be transported to the external heat exchanger effectively. On paper, this invention appears to have the potential to prevent tyres from overheating quite successfully. It should be able to be integrated into the subsystems of a haul truck. Advantages of this cooling method include its durability, the use of a common sump with the drive system and the provision of a heat sink away from the tyres themselves. As the secondary cooling circuit is located on the truck and not on the tyre itself, it can be bigger, more efficient and better protected. Other inventions which are attached only to the wheel assembly have been criticised for their lack of protection and poor performance. Furthermore, as the heat exchanger is located on the truck, other heat sources such as the electric motors and brakes will not interfere with the heat dissipation process. It would be ideal for the cooling method to employ the advantages of an external heat exchanger and not to deal with the rotating wheel-truck interface. Nonetheless, this invention appears to address this problem reasonably well with the oil cooling circuit and common sump. As the cooling circuit is isolated from the tyre chamber, it does not need to be pressurized and thus excessive leakage is avoided.

The major drawbacks of the invention would include a strict maintenance regime due to its complexity as well as making structural changes to truck and wheel assemblies. The most worrying would be the potential for harm at the pressurized interface between the tyre chamber and the ambient air at the rim where the cooling coils need to pass through. If not constructed properly there is potential for major damage to occur through a high pressure leak. Another point to note is that if the coils contain flaws, they may leak into the tyre and oil induced deterioration may occur. The invention could be improved by utilising a phase change for the primary working fluid to maximise the heat transfer potential if such a fluid was available.

2.4. Tyre Carcass Modifications

These patents generally propose an increase in the heat transfer area of the tyre by introducing modifications to the tyre carcass. Brunswick [38] presented a patent to utilise multi-cellular rubber tyres with two series of cells, extending both longitudinally and transversely. The objective was to provide a ventilation device to direct air from outside through the cells to cool the tire (Fig. (**13**)). Hsu [39] proposed a vehicle tyre, which included an outer tyre fastened to a rim. A series of hooks could secure the outer tyre to the rim. The inner tube also has a series of pegs raised from the tyre sidewall and provided air channels to carry heat away from the tyre (Fig. (**14**)). A patent described by Rayman [40] proposed changing the tyre structure itself to a two-piece tyre assembly. This new structure is described in depth and contains a removable tread belt (Fig. (**15**)) for installing about the circumference of a tire carcass. The radially inner surface of the tread belt and outer circumferential surface of the carcass had circumferentially extending grooves and ribs that could interlock. The grooves extend from a central region at the tyre tread to one of the lateral edges. Thus, the resultant venting sub-surface passages provided a convective cooling system for the two-piece tyre assembly. Experimental results for this cooling structure indicated drops of up to 40ºF at the carcass inner face and up to 30ºF at the interface between tread belt and tyre carcass. Although promising results have been achieved, the invention appears to be designed for passenger car tyres so it is unclear whether the ideas are still applicable on larger scale earthmoving tyres. Besides, when it comes to heavy trucks, strength and yielding point checks remain as other issues.

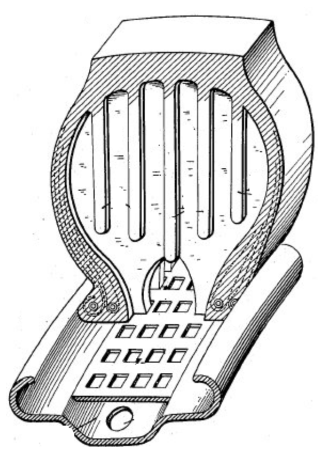

Fig. (13): Multi-cellular rubber tyre [38]

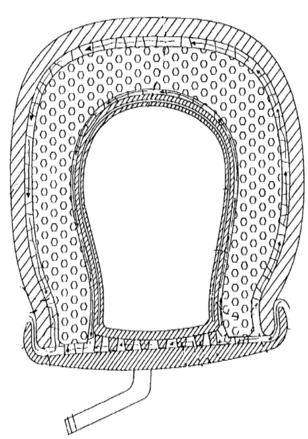

Fig. (14): Tyre with inner tube and hooks [39]

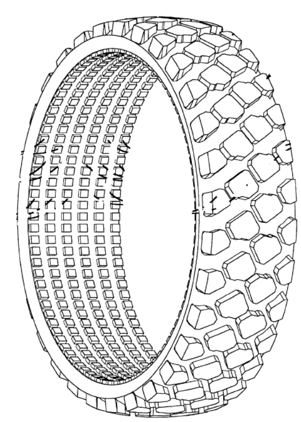

Fig. (15): Tread belt with grooves [40]

2.5. Heat Pipe Type Patents

These patents propose incorporating rotating heat pipe technology into the wheel assembly and thus utilising the existing centripetal forces to transport a heat transferring medium between two radial locations. A heat pipe is an attractive heat transfer device because it generally has no moving parts and is known to achieve a thermal conductance up to 500 times that of a solid copper rod of similar mass [41]. Experimental and analytical investigations have been completed incorporating a rotating heat pipe in a number of applications including turbine blades [42, 43] and automotive disk brakes [44, 45].

Ocone [19] suggested a cooling technique which strongly resembles that of a revolving heat pipe. A chamber is to be installed between the rim and hub of the wheel (Fig. (**16**)) which is to be evacuated apart from the working fluid. The heat transfer process is that of a heat pipe where the fluid contacting the inner surface of the tyre vaporises due to the high temperature. Due to centripetal forces the vapour is subsequently forced radially inward where the cooler ambient air condenses the working fluid. Now due to the increased density the working fluid is forced outwards by the centripetal force, creating a continuous cycle.

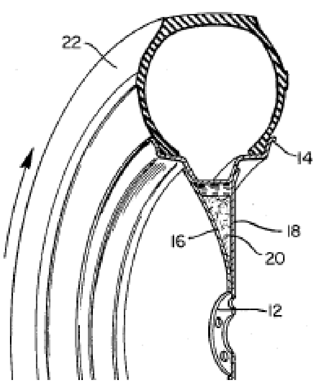

Fig. (16): Cross-section of wheel assembly [19]

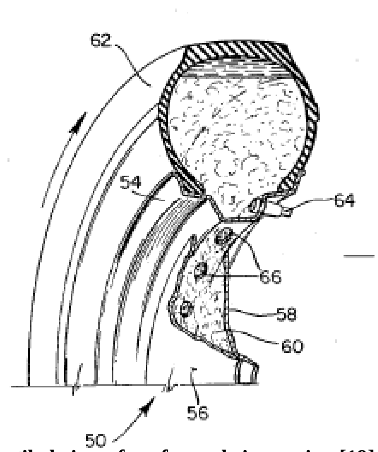

Fig. (17): Detailed view of perforated rim section [19]

The invention has three basic embodiments;

- the fluid cavity is contained within a web (Fig. (**16**))
- the fluid cavity is contained within a number of 'spokes'
- the outer surface of the rim has a series of perforations connecting the fluid cavity and tyre chamber (Fig. (**17**))

The first two methods are essentially identical apart from the shape of the fluid cavity. The advantage of using a series of spokes is that there will be an increased surface area for the working fluid to condense. This allows for more effective heat dissipation. It is asserted that the first method of a single web will provide a degree of wheel balancing to the assembly; however this would probably be a very minor effect on an earthmoving vehicle. Additionally, the fluid cavities are to be entirely evacuated apart from the heat transferring medium. In other words, there are no additional non-condensing gas molecules to impede the recirculating motion.

In terms of a working fluid, the inventor suggests that a more volatile liquid would be preferred, e.g. one that vaporises easily. It is also desirable for the fluid to possess a high value of latent (evaporation) evaporation heat. The wall structure of the fluid cavity must be considered and needs to be able to withstand the changes in internal pressure caused by the phase changes of the working fluid.

The third embodiment of the invention has perforations which connect the fluid cavity and tyre chamber, making the inside surface of the tread the outer radius of operation. This method has the advantage of allowing the heat transfer medium to make direct contact with the heat source (tyre tread). However, the fluid is exposed to the tyre chamber pressure and is free to interact with the inflating gas molecules. These two reasons mean that the heat transfer ability of the third method will actually be decreased compared to the first two.

This invention seems to have reasonable potential in tyre cooling applications. It proposes incorporating a proven method of cooling with minor structural changes to the wheel assembly. An appropriate working fluid should be found to operate between the given temperature limits. As part of the critical assessment, several shortcomings were also identified which need to be addressed for this invention to be viable on a practical level.

- In the first two embodiments; in order for the working fluid to vaporise on the tyre rim, heat transfer is required to occur from the tread across the tyre chamber using the inflating gas. This may not be feasible as this is largely based on free convection using a relatively poor heat transport medium.
- The heat sink in all embodiments is the ambient air passing over the tyre rim. There may not be a strong driving force for heat dissipation; especially in hot underground conditions
- In the third method, the working fluid is free to interact with the air inside the chamber, introducing frictional problems and reducing the effectiveness of the fluid circulation.
- Perforated version is less structurally sound - a collision may cause the tyre chamber to burst.

3. Current and Future Developments

Of the patents reviewed, the three techniques presented above appear to have the most potential for effective cooling. The lessons learned from assessing these methods can be applied for a future proposed cooling method. Three major points for discussion are highlighted below.

(i). Phase Change: These patents have highlighted the fact that a fluid has its greatest potential for heat transfer when it undergoes a phase change. Thus it is necessary to select a working fluid which vaporises and condenses within the given temperature limits and pressure conditions. If a single phase system is used then the possible heat transfer is significantly reduced, rendering the cooling technique ineffective.

(ii). Heat Exchanger Location: It would be ideal for the heat exchanger to be entirely localised to the wheel assembly as it avoids the problem of rotating connections. Nevertheless, if the heat exchanger is located on the vehicle, it is more protected and can be larger and more efficient. Another advantage of a heat exchanger on the vehicle is that it can service all wheels in parallel, reducing the need for replication on all wheel assemblies.

(iii). Heat Sink: Many researchers suggest ambient air as the direct heat sink for the wheel assembly. However, if a cooler heat sink or similar device is utilised there will be more drive for heat dissipation from the tyre, leading to a more effective cooling technique.

As outlined previously, heat management in earthmoving tyres is critical to the production of any mine site. An effective method of cooling is required to actively maintain the internal temperatures in tyres to extend tyre lifetimes and remove some of the operating restrictions for haul trucks. One of our research projects focuses on incorporating an effective cooling strategy to improve the tyre heat dissipation. Small scale experiments are being formulated to test the effectiveness of this cooling strategy in an actual tyre and numerical models of the heat transfer are to be created. Nonetheless, elaborating on the details of our numerical and experimental techniques is left for a future report.

Acknowledgments

The third author, the scholarship holder, acknowledges the support provided by The University of Queensland in terms of UQILAS, Endeavor IPRS, and School Scholarship.

Note added in proof. We are also indebted to Prof. K. Zaman, the editor, for providing us with a comprehensive list of relevant patents. His help and support has significantly improved our initial draft of the paper.

References

[1] Bridgestone, *Heavy Duty Off-The-Road Tyre Application Training*. 2007, Bridgestone Tyres. p. 139.

[2] B.S. Oh, Y.N. Kim, N.J. Kim, H.Y. Moon, and H.Y. Park, Internal Temperature Distribution in a Rolling Tire, Tire Science and Technology, vol. 23(1), pp. 11-25, 1995.

[3] P. Kainradl and G. Kaufmann, Heat Generation in Pneumatic Tires, Rubber Chemistry and Technology, vol. 49(3), pp. 823-861, 1976.

[4] Y.J. Lin and S.J. Hwang, Temperature prediction of rolling tires by computer simulation, Mathematics and Computers in Simulation, vol. 67(3), pp. 235-249, 2004.

[5] A. Le Gal, X. Yang, and M. Kluppel, *Sliding friction and contact mechanics of elastomers on rough surfaces*, in *Lecture Notes in Applied and Computational Mechanics*, P. Wriggers and U. Nackenhost, Editors. 2006. p. 253-260.

[6] B.N.J. Persson, Theory of rubber friction and contact mechanics, Journal of Chemical Physics, vol. 115(8), pp. 3840-3861, 2001.

[7] H.R. Berger and G. Heinrich, Friction effects in the contact area of sliding rubber: A generalized Schallamach model, KGK-Kautschuk und Gummi Kunststoffe, vol. 53(4), 2000.

[8] M. Barquins, Mechanisms of dry friction and wear of elastomers. Applications to the running and wear of tires on road surfaces, Mecanismes du frottement sec et de l'usure des elastomeres. Applications au roulement et a l'usure des pneumatiques sur les revetements routiers, (158), pp. 53-67, 1988.

[9] S.H. Yeow, M. El-Sherbiny, and T.P. Newcomb, Thermal Analysis of a Tyre During Rolling or Sliding, Wear, vol. 48(1), pp. 157-171, 1978.

[10] M.J. Otto, E.T. Steyn, and F. Elkink, Heat generation in textile tyre cords, KGK-Kautschuk und Gummi Kunststoffe, vol. 50(3), pp. 192-197, 1997.

[11] B.T.F. Chung, P.C. Yang, M.H.N. Naraghi, and D.J. Schuring. *HEAT TRANSFER IN ROLLING TIRES*. Seattle, WA, USA: Pineridge Press, Swansea, Wa, 1983.

[12] B. Yavari, W.W. Tworxydlo, and J.M. Bass, Thermomechanical model to predict the temperature distribution of steady state rolling tires, Tire Science & Technology, vol. 21(3), pp. 163-178, 1993.

[13] H.C. Park, S.K. Youn, T.S. Song, and N.J. Kim, Analysis of temperature distribution in a rolling tire due to strain energy dissipation, Tire Science & Technology, vol. 25(3), pp. 214-228, 1997.

[14] T.G. Ebbott, R.L. Hohman, J.P. Jeusette, and V. Kerchman, Tire temperature and rolling resistance prediction with finite element analysis, Tire Science and Technology, vol. 27(1), pp. 2-21, 1999.

[15] S.K. Clark, TEMPERATURE RISE TIMES IN PNEUMATIC TIRES, Tire Science and Technology, vol. 4(3), pp. 181-189, 1976.

[16] P. Kainradl, G. Kaufmann, and F. Schmidt, Zusammenhang der Erwarmung von Lkw-Reifen der Grosse 11.00-20 mit den visco-elastischen Eigenschaften der verwendeten Gummi-Qualitaten, Kautschuk und Gummi Kunstsoffe, vol. 19, pp. 27, 1966.

[17] S.A. Bridgestone, 2002.

[18] P. Kainradl and G. Kaufmann, Viscoelastic properties of truck tire compounds and the related heat build up, a meeting of the Rubber Division, 1971.

[19] L.R. Ocone, Wheel Assembly with Tire Cooling Means, US Patent 3675699, 1972.

[20] R. Gollert, Cooling Device for Tires, US Patent 1956739, 1934.

[21] J.J. Groezinger and G.A. Anders, Tire Cooling by Fluid Transfer Element, US Patent 4620580, 1986.

[22] L.C. Mote, Method of and Means for Prolonging the Life of Pneumatic Tires, US Patent 2948321, 1960.

[23] C.B. Isham, Tire Cooling Arrangement, US Patent 2538563, 1948.

[24] C.M. Manly, Vehicle Tire, US Patent 1780306, 1930.

[25] A.B. Craig, Cooling Device for Pneumatic Tires, US Patent 1049677, 1913.

[26] F.O. Skidmore, Tire Cooling, US Patent 3270794, 1964.

[27] F.O. Skidmore, Tire Cooling, US Patent 3414036, 1966.

[28] F.O. Skidmore, Tire Cooling Structure, US Patent 4381026, 1983.

[29] M. Preiss, Air guiding arrangement for a motor vehicle front end, US Patent 6033010, 2000.

[30] A. Morelli and N. Di Giusto, A device for reducing the form drag of vehicles, EP0738650, 1996.

[31] H. Burst, Aerodynamic brake cooling spoiler, US Patent 4810021, 1989.

[32] J.H. Becker, Tire Spray Control Device, US Patent 5100177, 1989.

[33] H. Weisbarth, A. Hack, and R. Tiefenbacher, Front end covering for a motor vehicle, US Patent 5511847, 1996.

[34] J.H. Becker, Air duct for cooling rotating tires, US Patent 6260911, 2001.

[35] E. Bobard, Ballasting and inflation apparatus, US Patent 4298047, 1981.

[36] C. King, Tire cooling device and method of cooling, US Patent 3708006, 1973.

[37] C.P. Hart, Tire Cooling System and Method, US Patent 4343338, 1982.

[38] J. Brunswick, Means for Cooling Multicellular Rubber Tires, US Patent 2166927, 1939.

[39] S. Hsu, Vehicle Tire with Air Circulation Arrangement, US Patent 6343635, 2002.

[40] W.E. Rayman, Two Piece Tire with a Convective Cooling System, US Patent 6619351, 2003.

[41] D. Chisholm, The heat pipe Mills and Boon. London, 1971.

[42] J. Ling, Y. Cao, and W.S. Chang, Analyses of Radially Rotating Heat High-Temperature Heat Pipes for Turbomachinery Applications, Journal of Engineering for Gas Turbines and Power, vol. 121(2), pp. 306-312, 1999.

[43] Y. Cao, W.S. Chang, and C.D. MacArthur, *An Analytical Study of Turbine Disks Incorporating Radially Rotating Heat Pipes*, in *American Society of Mechanical Engineers (Heat Transfer Division)*. 1998, ASME: New Jersey.

[44] S. Maezawa, Y. Susuki, and A. Tsuchida. *Heat Transfer Characteristics of Disk-Shaped Rotating Wickless Heat Pipe*. in *IVth International Heat Pipe Conference*. London, UK: Pergamon Press, 1981.

[45] S. Maezawa, M. Takuma, and A. Tsuchida, *Application of Disk-Shaped Rotating Heat Pipe to Brake Cooling*, in *14th International Centre for Heat and Mass Transfer*, Hemisphere Publishing Corporation: Yugoslavia, 1982.