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AIR PERMEABILITY INVESTIGATION TOWARDS AUTOMOTIVE TYRE PRESSURE SUSTAINABILITY AND LIFE SAVING

Sivaraos, M. J. Raguvaran, A. S. Dahlan, K. Kadirgama and M. A. Amran
Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Pahang, Malaysia
E-Mail: sivarao@utem.edu.my

ABSTRACT

One of the main reasons for major road accidents which often lead into loss of life's is the catastrophic tyre failure caused by vehicles running with improper tyre pressure. The phenomena where tyre loses pressure naturally and contracts over time is called air permeation, which is identified to be the main cause of tyre to deflate but rarely can be realised by naked eyes. Properly inflated tyres can safe tyre life up to 20% which is equivalent to nine months of its life span, save fuel from 4% to 10%, increase braking efficiency up to 20%, lightens steering system and ease self-steer. Therefore, this paper reveals the investigation findings by analysing the factors that affect the air permeation that eventually causes pressure loss in an automotive tyre. The experimentations were performed in both static and dynamic conditions where they were also tested with and without loaded situation to extract precise data of the pressure loss from tyre. The results show that no matter what type of tyre or condition it undergoes, it still experience pressure drop but at different rate subjected to air properties, temperature, tyre materials and mechanical fittings of the wheel.

Keywords: tyre pressure, pressure loss, air permeation, porous material, tyre air leak, tyre safety.

INTRODUCTION

Automotive tyres are basically made of natural and synthetic rubber where their hybridization acts as many role plays not only in providing comfort, but also ensure safety while it's rolling at different types of road conditions and operational temperature. The only medium that transfers the whole lot of vehicle load onto the road is tyre. As tyres supported by the wheels, it provides a cushion between the road and the vehicle suspension, provides traction for both acceleration and braking, resist lateral forces for safe cornering, stability and better handling. With the assistance of the air pressure inside them, tyres are responsible to support the overall weight of a vehicle too [1].

Automobile tyres naturally undergoes gas escapism upon several causes, which then requires regular inflating to replace the air loss in order to sustain proper tyre pressure. Tyre pressure drops mainly due to pressure lose or air escapism from the tyre. Besides tyre quality and tyre materials, improper tyre pressure is the main factors led to catastrophic tyre failure and eventually leads to major road accidents [2, 3]. Furthermore, the research finding also shows that every 20 kilopascal pressure drop in a tyre is equivalent of adding a 70kilogram person in to the car [4] which indirectly causes to excessive tyre wear and might result in serious road accidents due to poor control and stability of the car. Micro molecular gases can easily escapes to the atmosphere from a pressurized vessel through the interface fittings and absorption through porous materials. Studies also shows that an automobile tyre naturally releases about 10-20 kPa of pressure every month regardless of tyre brand used [4].

LITERATURE REVIEW

Besides tyres are punctured by sharp objects on the road, such as steel nails, the tyres do experience natural air leakage caused by its porous material and mechanical fitting of the wheel. This pressure leak is called air permeability. Since tyres are made of rubber hybridized and manufactured by combining of materials such as natural rubber, butadiene rubber, halo-butyl rubber, polyester cord and rubber coated fabrics which is a form of porous material, literally shows that even properly fitted tubeless tyres which are free of mechanical leaks can still have significant pressure loss via permeation [5,6] which shown in Figure-1. Over the time, air molecules would make their way through the maze of molecular chains and escape especially through the tyre sidewalls [7]. Other factors which contribute to tyre air permeation are the excessive operating temperature [8-11] and the existence of oxygen molecules in compressed air used for inflating the tyre. These molecules are much smaller than nitrogen and would eventually escape to the atmospheric through tyre wall. On top of that, portion of oxygen moisture would also evaporate causing pressure drop in the tyre [12].

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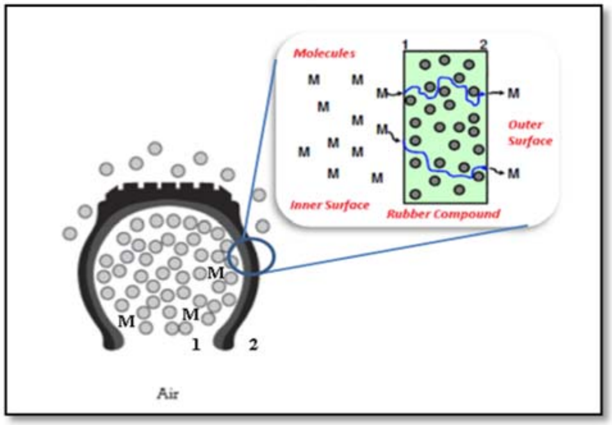

Figure-1. Molecule permeability in the rubber compound.

Even though most tyres look the same, but they are not when comes to its detail structures, particularly layers of liners. Most tyre manufacturers use “Butyl-Inner Layer” to improve the ability to retain best of its air pressure [13]. The permeability, Q is the product of mean diffusion coefficient, D and a function, S related to the solubility of the penetrant gas in the polymer; can be derived by equation (1):

$$Q = D \times S \quad (1)$$

The Solubility value *S* and the diffusivity value Dis proportional to tyre operating temperature, then the permeability Q would relatively increase with the rise of tyre temperature. The molecules shown as M in Figure-1, solubilizes at inner surface of tyre and finally diffuses through the rubber compound and evaporates through the tyre outer surface to atmospheric [14].

Temperature which promotes air permeability

On average, automobile tyre will lose seven to 14 kPa of air pressure per month in cool climate and more upon warmer months due to the air permeability behaviour of tyre materials which responds differently with temperature [7]. The tyre operating conditions subjected to cyclic deformations generating possible hysteresis to the spinning kinematics [15] and the energy loss due to this phenomenon consequently influences the coefficient of friction and the tyre temperature [16, 17]. Therefore, the heat is generated from the result of friction with the road surface when the rubber structure is under deformed condition [18] and this phenomenon ultimately result in increasing the tyre temperature.

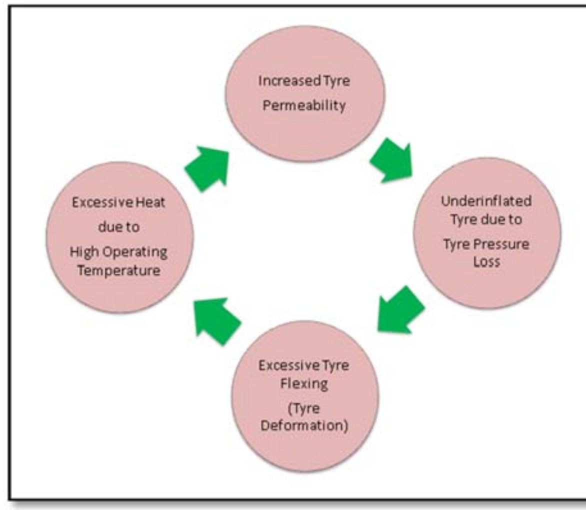

Figure-2. The tyre pressure loss operation cycle upon excessive heat.

Figure-2 reveals that, as the heat increases due to increased flexing on the sidewall of the tyre, it will proportionally increase the porosity resulting worse permeability. Therefore, this proves that a hotter tyre is more permeable and tends to experience greater pressure loses [12]. Moreover, excessive heat is accumulated inside the tyre once the vehicle is fully loaded and travel at higher speed. On a continuous driving, the tyre will reach its stagnant point where the temperature is brought to stop which is also called as “Saturation Temperature”, and the maximum allowed temperature for most tyres are limited to 125°C and would gradually decrease to 20°C within 10 minutes of rest [19].

Figure-3 witnesses the excessive heat concentration which takes place at the shoulder and sidewall of the tyre [20, 21] being subjected to load, acts as an absorber where it attracts heat more than other region in tyres during dynamic condition. The common tyre sidewall thickness is about 3 to 4 mm as compared to 15 to 20mm of its crown thickness [13].

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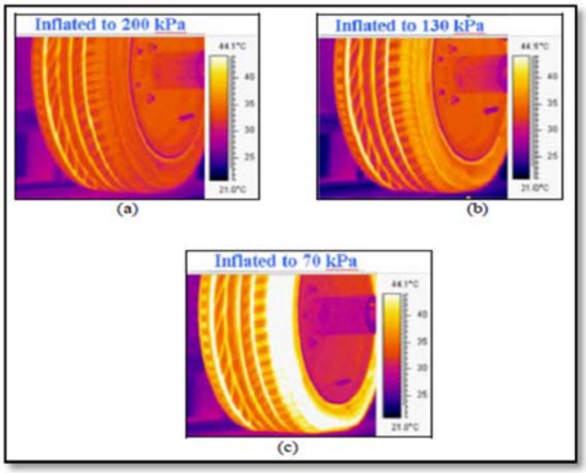

Figure-3. Thermal-imaging at different tyre pressure condition.

Properties of inflated air

Automotive tyres are usually inflated with compressed air available at gas/fuel stations. Basically, compressed atmospheric air contains Nitrogen (78%), Oxygen (21%), Argon (0.9%), and miscellaneous gases (0.1%) [22]. Since rubber is formed of porous material and not 100% impermeable, the pressurized air inside the tyre will seek equilibrium state with the atmospheric pressure outside the tyre boundary. Oxygen molecules are much smaller and humidified compared to Nitrogen. Thus, Figure-4 shows how oxygen molecules filled into the tyre will migrate in a faster rate through the tyre materials especially at sidewalls (75%), around the tyre bead (15%) and even through the valve stem (10%) of air leak [22].

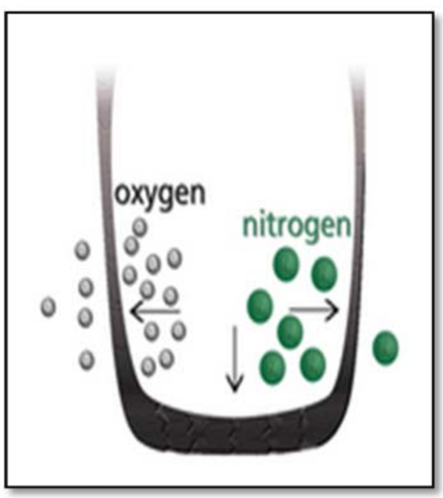

Figure-4. Permeability of oxygen and nitrogen molecules through tyre sidewalls.

Pressure leak through mechanical fittings

Both the inflating valve and rim flange can be corroded over the time due the oxygen contact at the internal and external part of them [23]. This is clearly shown in Figure-5, where the rough surfaces on the rim flanges and tyre beads might not be sealed properly causing additional air leaks. On the other hand, tiny spots of corrosion on rim would not allow the valve seat to be mounted properly on the rim valve seat and this situation worsens air escapism which caused pressure drop in tyre.

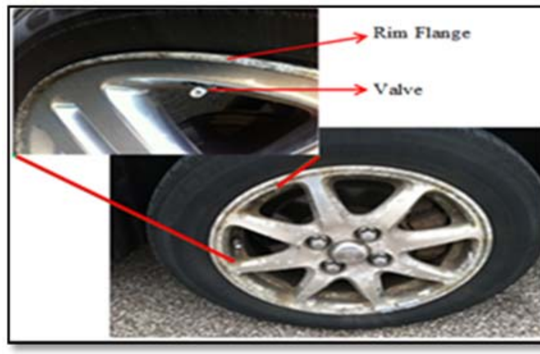

Figure-5. Corroded rim flange and valve.

METHODOLOGY

In order to measure and analyse the natural pressure drop of a tyre, two different ways were organized which is; static-unloaded and dynamic-loaded condition to study the deflation rate in both respective conditions. The tyres used for this were of the same widely commercialised (xx) brand with the aspect ratio 205/55R16 in similar conditions.

Static pressure test - unloaded condition

Wheel assembly with a brand new tyre and valve stem, mounted on a test rig as shown in Figure-6. The tyre was inflated with compressed air at 230kPa without any rotation, contact, or load applied to it and kept in a closed room with its room temperature of 25°C.

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Figure-6. Static pressure test for unloaded tyre.

The pressure drop of the tyre were measured and recorded every one month using pressure gauge exactly from the date the tyre was inflated and mounted on the rig. This test was conducted for five months continuously without any inflation.

Dynamic pressure testing - loaded condition

The tyres are also tested in a dynamic-loaded condition to differentiate and evaluate the pressure drop in both the condition. All the specification used during static-unloaded condition is maintained (new tyre and valve stem) but the differences are that the tyre is fitted in a road travelling car (Malaysian made Proton Perdana 2.0 litre, V6) as shown in Figure-7 where it weights about a ametric tonne. The tyres were initially inflated at 230kPa with compressed air.

Figure-7. Dynamic-loaded tyre test on a vehicle.

For this condition, only one out of four tyres was randomly chosen, namely front right tyre to be observed. The pressure drop of the tyre was observed and recorded of daily interval for every month using pressure gauge, exactly from the date the tyre was inflated and fitted on the vehicle. This test was conducted for five continuous months without any inflation. Temperatures of the tyres were also observed with thermocouple.

RESULT AND DISCUSSIONS

Static-unloaded tyre test

The observed Static-Unloaded Tyre Test is tabulated in Table-1. Subsequently, Figure-8 shows the plot where the pressure drop trend can be monitored.

Table-1. Observed pressure for static-unloaded tyre.

Month	**Pressure** (kPa)
1	230
2	227
3	223
4	220
5	217

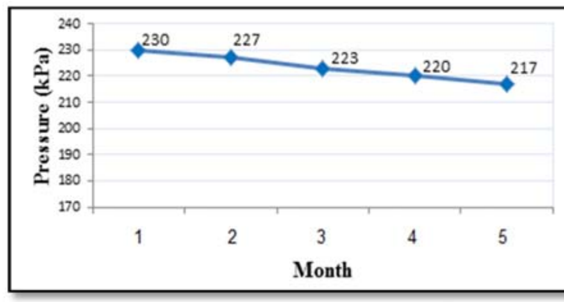

Figure-8. Pressure decrease over month.

The phenomena where the tyre experiences pressure drop gradually from the first until fifth month are represented in Figure-8, in which the data are tabulated in Table-1. This shows that tyres experiences pressure drop even at room temperature, without operating and load added to it, but ata smaller scale due to air permeation. It is also proven that a tyre with inflated air can permeates faster compared to tyre with inflated pure Nitrogen [24]. To treat the problem analytically by calculation, a few simplifying assumptions have been considered:

a) The inflated air contains only 80% of Nitrogen and 20% Oxygen.
b) The tyre inner-casing material is composed of *Butyl*layer with 1cm thickness.
c) The tyre is stored in ambient room temperature of 25°C.
d) The entire variables are at Standard Temperature and Pressure (STP).
e) The permeability of Oxygen is:

$$P_{O2} = 4.6\text{x}10^{-13} \frac{\text{cm}^3\ (\text{STP}).\text{cm}}{\text{cm}^2\ .\text{s. Pa}} \text{ at } 25°\text{C}$$

f) The permeability of Nitrogen is:

$P_{N2} = 1.6\text{x}10^{-13}$ $\underline{\text{cm}^3\ (\text{STP}).\text{cm}}$ at 25°C

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$cm^2.s.Pa$

The tyre (interior) is inflated to $p_{total\ interior} = 230kPa$
$= 2.3x10^5 Pa$
$N_2 = 80\% = 0.8$
$O_2 = 20\% = 0.2$

The Atmospheric (exterior) pressure to $p_{exterior} = 1$ bar
$= 1x10^5 Pa$
$N_2 = 80\% = 0.8$
$O_2 = 20\% = 0.2$

$\Delta p_{N2} = (2.3 - 1) \times 0.8 = 1.2 \text{ bar} = 1.04x10^5 Pa$

The flux of gas through the tyre casing per unit of time and surface area, $\dot{n}''$:

$$\dot{n}'' = P_i \times \frac{P_{i1} - P_{i2}}{l} \quad (2)$$

$$\dot{n}'' = Pi \frac{\Delta p_{N2}}{l} = 1.6 \times 10^{-13} \times \frac{1.04x10^5}{1}$$

$$= 1.66x10^{-8} \frac{cm^3 (STP)}{cm^2.s}$$

$\Delta p_{O2} = (2.3 - 1) \times 0.2 = 0.26 \text{ bar} = 2.6x10^4 Pa$

$$\dot{n}'' = Pi \frac{\Delta p_{O2}}{} = 4.6x10^{-13} \times \frac{2.6x10^4}{l1}$$

$$= 1.20x10^{-8} \frac{cm^3 (STP)}{cm^2.s}$$

Hence the total outward flux for inflation with air,

$\dot{n}''_{total\ air}$ is obtained by:

$$\dot{n}''_{total\ air} = \dot{n}''_{N2} + \dot{n}''_{O2}$$
$$= 1.66x10^{-8} + 1.20x10^{-8}$$
$$= 2.9x10^{-8} \frac{cm^3 (STP)}{cm^2.s}$$

Based from the above, it is clear that tyre which has been inflated with air at 230kPa has the outward flux inflation rate of:-

$(\dot{n}''_{total\ air} = 2.9x10^{-8} \frac{cm^3 (STP)}{cm^2.s})$.

deflates more rapidly compared to tyres inflated with pure Nitrogen at 230kPa which has the outward flux inflation rate [24] of :-

$(\dot{n}''_{total\ nitrogen} = 1.3x10^{-8} \frac{cm^3 (STP)}{cm^2.s})$

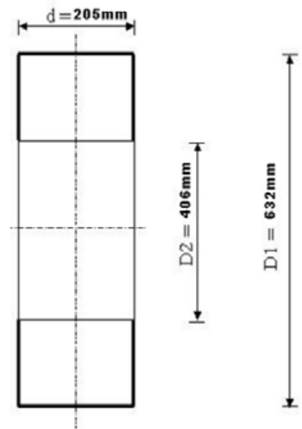

Figure-9. Tyre section measurements.

The gas flows through the tyre surface $A_{exchange}$, is given by:

$$A_{exchange} = 2 \cdot \pi \cdot \left[\left(\frac{D_1}{2} \right)^2 - \left(\frac{D_2}{2} \right)^2 \right] + 2 \cdot \pi \cdot (D_1 \cdot d) \quad (3)$$

$$A_{exchange} = 2 \cdot \pi \cdot \left[\left(\frac{632}{2} \right)^2 - \left(\frac{406}{2} \right)^2 \right] + 2 \cdot \pi \cdot (632 \cdot 205)$$

$= 11.8x10^3 \ cm^2$

While the volume, V is obtained by :

$$V = \pi \cdot \left[\left(\frac{D_1}{2} \right)^2 - \left(\frac{D_2}{2} \right)^2 \right] \cdot d \quad (4)$$

$$V = \pi \cdot \left[\left(\frac{632}{2} \right)^2 - \left(\frac{406}{2} \right)^2 \right] \cdot 205$$

$= 37.8x10^{-3} \ m^3$

As t_m can be described as number of seconds in a month, which is:

$$t_m = 3600 \frac{seconds}{hour} \times 24 \frac{hour}{day} \times 30 \frac{days}{month}$$

$$= 2.6x10^6 \frac{seconds}{month}$$

Therefore, the outward flux of gas (tyres inflated with air) in a month can be estimated. Since, tyres inflated with air which has the rate of outward flux inflation of;

$$\dot{n}''_{total\ air} = 2.9x10^{-8} \frac{cm^3 (STP)}{cm^2.s}$$

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$$\dot{n}_{totalair} = \dot{n}''_{totalair} \times A_{exchange} \quad (5)$$

$= (2.9x10^{-8}) \times (11.8x10^{3})$

$= 3.4x10^{-4} \dfrac{cm^3 (STP)}{S}$

$$n_{month\ air} = \dot{n}_{total\ air} . t_m \quad (6)$$

$= (3.4x10^{-4}) \times (2.6x10^{6})$

$= 884 cm^3$ (STP)

By using the *Ideal Gas Law*:

$$p.V = n.R.T \quad (7)$$

and the volume of a mole V_m, of an ideal gas is given by:

$$V_m = 22.414 \ \frac{l}{gmol}$$

Consequently the number of moles, n of gas initially contained inside the tyre casing can be obtained by:

$$n, \text{moles}_{air\ initial} = \frac{p_{initial} . V}{R . T}$$

where
Initial tyre pressure, $p_{initial}$ = 2.3bar = $2.3x10^5 Pa$
Volume, $V = 37.8x10^{-3}\ m^3$
Ideal or Gas constant, $R = 8.3145 \dfrac{J}{gmol. K}$

Temperature in Kelvin, T = 25°C + 273.15 = 298.15 K

As the values obtained above can be substituted into the formula:

$$n, \text{moles}_{air\ initial} = \frac{(2.3x10^5)x(37.8x10^{-3})}{(8.31451) \times (298.15)} = 3.507 \text{ gmol}$$

Thus, the number of moles lost from the tyre casing in a month is obtained by:

$$\text{Moles}_{air\ out\ per\ month} = \frac{n_{month\ air}}{V_m} \quad (8)$$

$= \dfrac{884x10^{-3}}{22.414}$

$= 3.9x10^{-2}$gmol

Therefore the final pressure, p_{final} of the tyre after 1 month is given by:

$$p_{final} = \frac{(\text{moles}_{air\ initial} - \text{moles}_{air\ out}) . R . T}{V} \quad (9)$$

$= \dfrac{(3.507 - 3.9x10^{-2}) \times 8.31451 \times 298.15}{37.8x10^{-3}}$

$= 2.27x10^5 Pa$

= 227kPa

From the analysis, it reflects that in the case of tyre been inflated with air even at static unloaded tyre condition, the internal pressure will still decrease about 3kPa or 1.3% over a month period and the pressure drop rate might vary depends on the tyre size.

Dynamic-loaded tyre test

The observed Dynamic-loaded Tyre Test is tabulated in Table-2. Subsequently, Figure-10 shows the plot where the pressure drop trend can be monitored.

Table-2. Observed pressure for dynamic-loaded tyre.

Month	**Pressure** (kPa)	**Mileage** (km)
1	230	0
2	210	464
3	195	575
4	182	690
5	165	1150

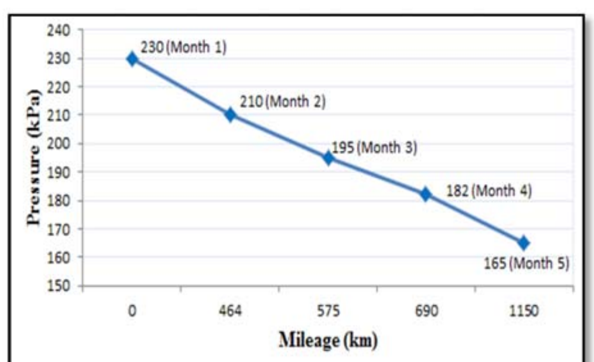

Figure-10. Pressure decrease over month and mileage.

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The phenomena where the tyre experiences pressure drop gradually from first up to fifth month in a larger scale, losing 10-20kPa per month as the vehicle travels more is represented in Figure-10 in which the data are correlated in Table-2. During the initial stages of the tyre operating condition, tyre temperature are noticed to be rising gradually too and become static which can be described as "Stagnation Point" at 44.7^{0}C for the front tyre and 41.8^{0}C at rear tyre as observed in Figure-11. Front tyres experience higher heat concentration due to the excessive load from the car's engine compartment as it is a front-engine car. It is very obvious that pressure drops more in a dynamic-loaded tyre test compared to static-unloaded tyre test condition. This is mainly because of the effect of operating temperature and load on the tyre. As the inflation pressure decreases, the temperature will increases since lower inflation pressure results in more deformation in the tyre rubber surface. This situation generally increases normal load on a tyre that eventually increases elastic deformation and the total strain energy density resulting in temperature rise [25] and therefore, proportionally increases the porosity resulting worse permeability which ultimately providing enough space for air leakage over time.

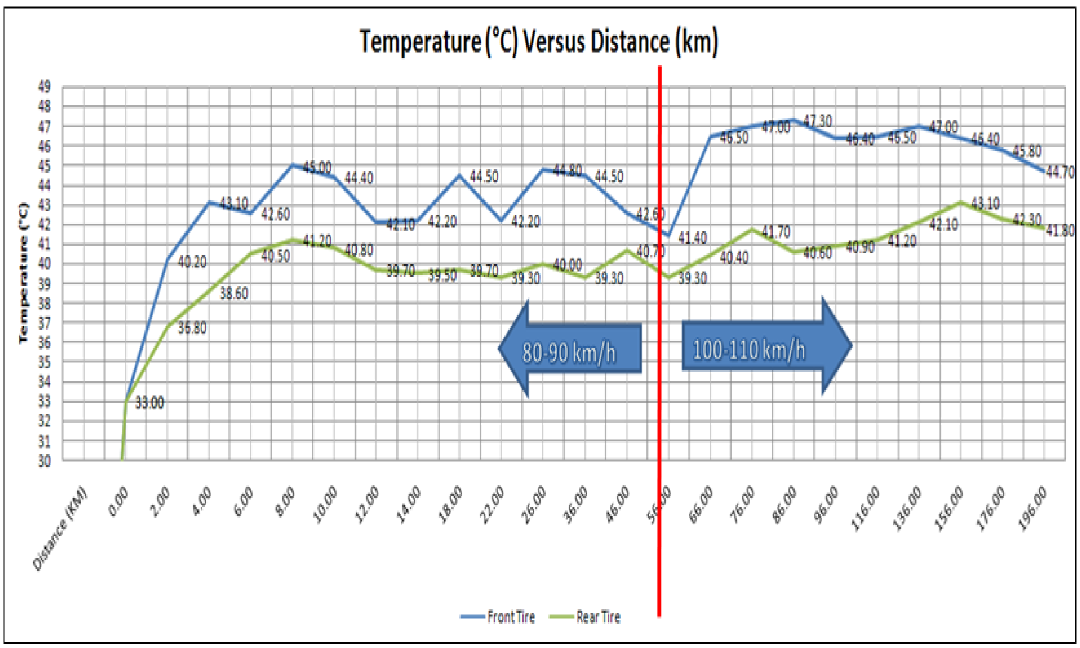

Figure-11. Temperature variance of tyre over distance travelled (Initial stage).

CONCLUSIONS

In this research, the factors that affects the air permeation that causes natural pressure loss to the tyre has been critically investigated and it shows that a normal passenger car tyre experience pressure drop both in static-unloaded and worse still during dynamic-loaded condition. At static-unloaded tyre condition, the tyre pressure drops mainly because of air permeation by means of inflating via compressed air which have the properties of Oxygen molecules but during dynamic-loaded condition; pressure drops more due to increased air permeability upon excessive operating temperature and with the presence of load. Therefore, this research gives an important response and valuable outcome in order to develop a reasonable solution for tyre to retain its pressure and literally minimizing the rate of air permeation which causes pressure loss at any circumstances.

Nomenclature

kPa	Kilopascal
psi	pounds per square inch
Q	Permeability
D	Coefficient of Diffusion
S	Solubility
l	Tyre Casing Material Thickness
M	Molecule
O_2	Oxygen
N_2	Nitrogen
STP	Standard Temperature and Pressure
$\dot{n}''$	Rate of outward flux inflation

t_m	Number of seconds in a month
A	Surface
p	Pressure
V	Volume
V_m	Volume of mole
n	Number of moles
R	Ideal or Gas constant
T	Temperature (°C)

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