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# Thermodynamic analysis of an automobile brake system

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**ABSTRACT**

Energy and exergy analyses of an automobile's air-ducted disc brake system were performed in the current study. The experimental system consisted of the brake disc, calliper, linings, the electric motor to drive the brake disc, and a hydraulic pump to provide the oil pressure required to activate the brake unit. To simulate the braking process, the force is applied to the rotating brake disc at different brake pressures and the temperature change on the disc due to the braking action was measured. The braking system was evaluated thermodynamically by using these measurements obtained. The ideal brake force values were found around 200ºC when continuous braking was adopted in the brake test. It was also noted that the brake force was decreased, and the braking process was weakened at the temperature of 250ºC and above. Exergy destructions by the braking process were also calculated.

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## 1. INTRODUCTION

One of the most important active safety systems in vehicles is the brake system. Continuous improvement efforts are carried out on brake systems to ensure safe and secure driving. Variations occur in the braking force due to the heat generated by friction in the brake system. The changes in the frictional properties of the discs, lining, etc., parts in the brake system and the loss of the properties of the elements in the brake system also affect the brake performance.

Bayrakçeken and Düzgün stated in their study that braking performance is one of the most critical factors affecting vehicle safety to stop the vehicle safely, and the temperature and stopping distance in the brakes are some of the essential indicators of braking performance [1].

Temperatures in the brakes are also affected by the disc and lining materials used. Etemoğlu et al. stated in their study that the sudden break in vehicles and heating occurs in the disc brake systems. When high temperatures are reached, corrosion may occur in the brake lining. This situation affects the brake performance negatively [2].

Çavdar et al. reported that high temperatures generated during braking cause a decrease in brake force, brake weakening, premature wear, and evaporation of brake fluid, bearing failures, and many undesirable conditions on the vehicle thermal cracks. As a result, braking performance is negatively affected [3].

Braking systems operate with the friction principle, which transforms the vehicle's kinetic energy into thermal energy (heat) through friction. High temperatures adversely affect the disc and lining material properties and cause the surfaces to glaze. As a result, as the friction force between the disc and the lining decreases, various malfunctions occur in the braking system. In this regard, the coefficient of friction between the disc and the brake lining decreases. The reduction in the friction coefficient eventually causes the braking force to be negatively affected [3]

Düzgün and Yıldız observed in their experimental study that the heat generated in the brake system changed in proportion to the mass and speed of the vehicle. When the amount of heat generated by friction during braking reaches high values, it creates glare, glass formation, or thermal cracks on the disc surfaces over time. They also stated that the wear on the disc and lining surface increased, and the amount of wear also changed based on the lining and brake disc material used [4].

In his experimental study, Rudolf stated that the performance loss (fading) due to warming could change the brake force [5]. He said that one of the biggest problems in the vehicle brake system was that when the temperature of the linings rose above specific values (temperatures from 250 °C to 315 °C and above) due to friction, the linings started to slide as the contact loose.

Erdem and Altıparmak investigated the effect of increasing brake disc temperature on braking performance. For this purpose,

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braking distance tests that are the braking performance criteria were carried out [6].

There are close to each other threshold values in the literature regarding the loss of brake effectiveness due to the temperature increase in the brake disc. Satapathy et al. classify efficiency losses as 'load-related efficiency loss', 'speed-related efficiency loss' and 'temperature-related efficiency loss'. They also stated that temperature-related efficiency loss would manifest significantly starting from 370 ºC on disc brakes [7]. Bijwe et al. emphasized that brake discs that rise to temperatures between 300-400 ºC may cause a loss of effectiveness [8].

Aleksendric and Duboka noted that temperatures around 400 ºC are the threshold for loss of effectiveness [9]. If the disc temperatures exceed 600 ºC, the brake efficiency will be lost entirely due to the decreased friction coefficient between the brake disc and the lining. Lingman recorded similar threshold temperatures [10].

Dias and Balestrieri investigated the performance of thermal systems according to the 1st and 2nd laws of thermodynamics. Energy and exergy efficiencies of thermal systems; They stated that it is one of the critical decision parameters in the design of the systems, the selection of the systems, and the determination of the system's operating conditions.[11].

Energy analysis gives information about the whole system, deals with the quantity of power, and does not consider the losses that occur from irreversibility (entropy production) in the system. The second law of thermodynamics analyzes the evaluation of energy degradation, entropy production and the possibility of doing work during a process. Except in reversible systems, exergy (availability) is not conserved like energy. A part of the exergy is destroyed due to irreversibility in the system (exergy destruction), a part of it is thrown into the environment from the system boundaries (exergy loss) [12].

Dinçer and Rosen defined exergy as the maximum amount of work produced by a system or a flow of matter or energy when it comes to equilibrium with a reference environment Exergy measures the system's potential or flow to cause change due to not being entirely in stable balance relative to the reference environment. Exergy is not subject to a conservation law. Instead, exergy is consumed or destroyed due to irreversibility in any actual process. The exergy consumption during an operation is proportional to the entropy created due to the irreversibility associated with the process [13].

In this study, the heat energy value resulting from the high temperatures in automotive brake systems was calculated and examined in terms of thermodynamics. There are many factors in determining brake performance. One of these factors is the decrease in brake performance due to increased temperature.

## 2. MATERIAL AND METHOD

Experimental setup details for measurement test device and brake system are investigated in the first section. The energy analyses and energy and exergy analyses are separately given in the second part with thermodynamics equations.

### 2.1. Experimental Setup

An experimental setup was designed to perform tests under the conditions specified in Turkish Standards of 555 and 9076 [14]. The friction coefficient and the brake force of the linings can be examined under the influence of parameters such as different speeds, temperature, and pressure. The brake force tester enables establishing relations between friction coefficient and temperature, brake force and temperature, and friction coefficient vs time and temperature graphs.

In the friction coefficient tester shown in Figure 1, a three-phase electric motor with a power of 5.5 kW and 1400 rpm was used to rotate the disc. A transmission shaft of Ø 30 mm was used to transmit the motion obtained from the electric motor. It aimed to prevent the shaft from swinging by placing two bearings.

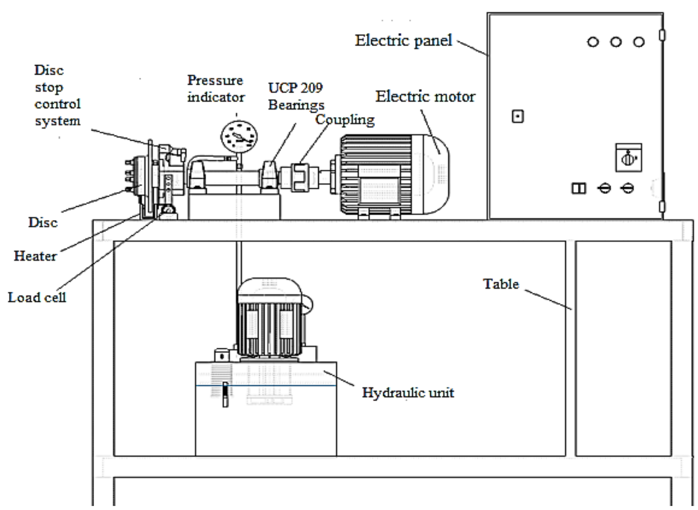


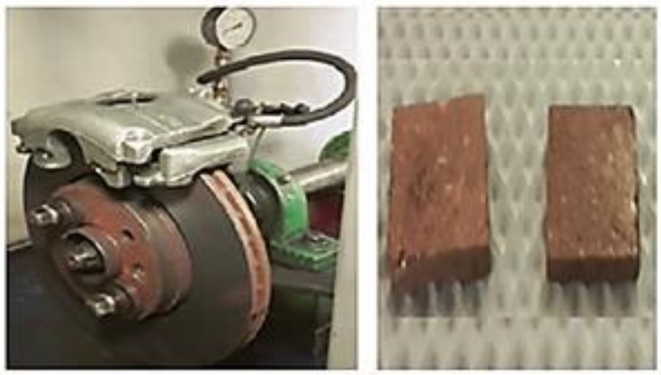

Fig 1. Schematic view of the brake force measurement test device [14].

The circular motion from the electric motor was transferred to the disc through the shaft at the desired round per minute (rpm) values using an inverter. The speeds were in the range of 0 to 1400 rpm. The computer program can control the speed of the electric motor.

The desired pressure can be applied to the brake disc using the hydraulic unit in the test system. During the test, a pressure control valve was placed between the piston and the hydraulic motor to prevent pressure fluctuations and keep the pressure constant at the desired value.

In this study, an air channel disc was used. Grinding and cutting operations prepared the linings suitable for the calliper piston in the brake tester.

Brake discs used in the experiment are defined as the elements that provide the transfer of the brake force applied for friction brakes to the disc or drums connected to the wheels of the vehicles by friction TS 555, Brake Lining Properties and Standards linings. Brake linings under TSE standards were used in the experiment. The lining was prepared in appropriate dimensions by performing cutting and grinding operations by the dimensions of the calliper piston specially made in the brake test setup. In Figure 2, the pictures of the lining used in the experiment are given.

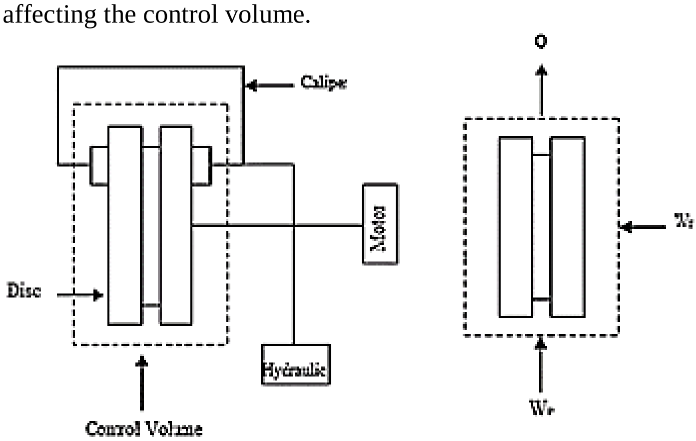


(a) (b)

Fig. 2. a) Brake disc, and b) Brake lining

The air-cooled brake disc was used in the brake force measuring device. Experiments were carried out at different brake pressures for the vehicle speeds of 60, 80, 100 km/h. Experiments were conducted by continuously increasing the temperature values for other brake pressures at each disc speed. Brake force values were measured for each temperature versus time. Temperature limit values were increased from 50 ºC to 400 ºC, and the brake force values were recorded at 50 ºC intervals.

The elements in the brake system are shown in Figure 3(a). The motor rotates the disk continuously. The disc is forced to stop using the hydraulic unit. Figure 3(b) addresses the parameters affecting the control volume.




(a) (b)

Fig. 3. Brake system; (a) Schematic of the system elements, (b) Energy balance on the control volume.

## 2.2. Energy and Exergy Analysis

### 2.2.1. Energy Analysis

The first law of thermodynamics deals with the conservation of energy. It states that the net change in the total energy in the control volume for a closed system during a process is equal to the difference between the total energy entering the design and the total energy leaving the system. The general energy equation is given in Equation (1).

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{sis}}{dt} \tag{1}$$

$$\dot{Q}_{net} - \dot{W}_{net} = \frac{mc_p dT}{dt} \tag{2}$$

Where $\dot{Q}_{net}$ and $\dot{W}_{net}$, respectively, are net heat and network rates.

$$\dot{Q}_{net} = \dot{Q}_{in} - \dot{Q}_{out} \tag{3}$$

$$\dot{W}_{net} = \dot{W}_{in} - \dot{W}_{out} = \left(\dot{W}_P + \dot{W}_T\right) \tag{4}$$

The pressure applied to the system and the work done by the electric motor rotating the disc is shown in Equation (5) and Equation (6).

$$\dot{W}_P = \int P d\mathcal{V} = P \int d\mathcal{V} = P\mathcal{V} \tag{5}$$

$$\dot{W}_T = F.V \tag{6}$$

Where $\mathcal{V}$ lining volume (m$^3$), brake pressure (N/m$^2$), $F$ power of electric motor (W) and rotational speed of the electric motor (m/s).

#### 2.2.2. Energy and Exergy Analysis

Exergy is the maximum work a system can do in a given state. Exergy analysis determines the magnitude of energy losses in each component to reveal ways of improvements that can be made. The general exergy equation of the fluid is the sum of chemical, potential kinetic and physical exergy as in Equation (7) [15].

$$\dot{Ex} = \dot{Ex}^{PH} + \dot{Ex}^{KN} + \dot{Ex}^{PT} + \dot{Ex}^{CH} \tag{7}$$

Chemical, potential and kinetic exergy are neglected in the study. The exergy balance for closed systems is given in Equation (8) and derived as in Equations (9) to (12).

$$\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} - \sum \dot{E}x_d = 0 \tag{8}$$

$$\dot{Ex}_{ısı} - \dot{Ex}_{iş} = \dot{Ex}_d \tag{9}$$

$$\dot{Ex}_{ısı} = \sum \left(1 - \frac{T_0}{T}\right) \dot{Q}_k \tag{10}$$

$$\dot{Ex}_{iş} = \left(\dot{W}_P + \dot{W}_T\right) \tag{11}$$

$$\dot{E}x_d = -\left(1 - \frac{T_0}{T}\right).\dot{Q} + \left(\dot{W}_P - \dot{W}_T\right) \tag{12}$$

$T_0$ in the equations is the ambient temperature, which is the reference temperature considered a dead state. In this study, the $T_0$ value of the environment was taken as 25 °C.

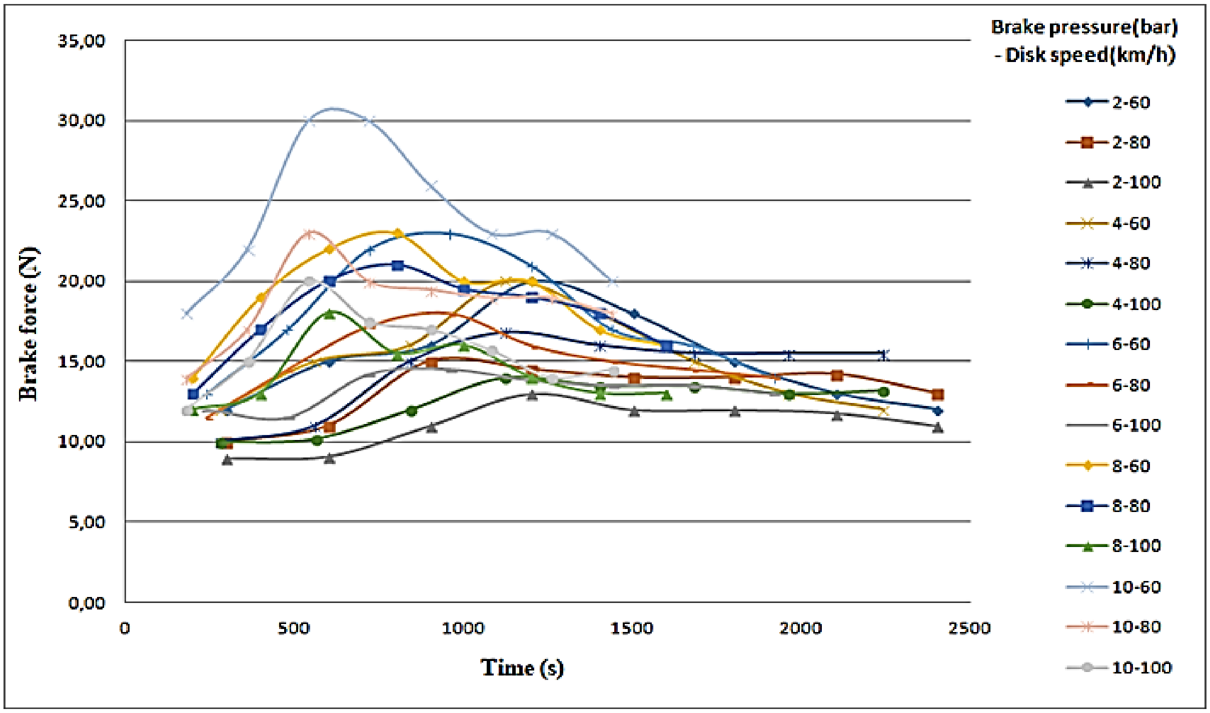



Fig. 4. Change of brake force over time according to brake pressure and disc speed.

## 3. RESULTS

The brake force values obtained at different disc speeds and brake pressures in the car were evaluated by exergy and energy analysis.

### 3.1. Experimental Findings

Measurements were obtained from the experimental system given in Figure 1. The brake force values were measured at different vehicle speeds and braking pressures depending on the temperature effect in specific periods. Measurements were taken at vehicle speeds of 60, 80, 100 km/h and in the different brake pressures of 2, 4, 6, 8, 10 bar. Subsequently, the variation of the brake force with time was obtained. Temperature values were experimented with starting from 0 °C to 400 °C with 50 °C intervals. The findings of the experimental results are given in Figure 4.

When Figure 4 from ref [16] is examined, it is seen that the braking force value reached maximum levels in approximately nine minutes for 10 bar brake pressure and 60 km/h vehicle speed, and after this point, it showed a decreasing trend. There is a similar trend for other measurement parameters. This decrease is the temperature increase caused by the friction between the disc and brake lining. As a result of the temperature rise, slipping occurs between the disc and the brake lining due to the glassy surface formation, and for this reason, the friction coefficient decreases. In addition, when we examine the brake force values obtained at different speeds, it is observed that there were more fluctuations in the brake force graphs obtained at higher speeds. The reason for this can be stated as the constant change of temperature as a result of the formation of more air circulation in the experimental environment with the increase of speed [16]. The present measurement values that give the temperature change of the disc are shown in Figure 5.

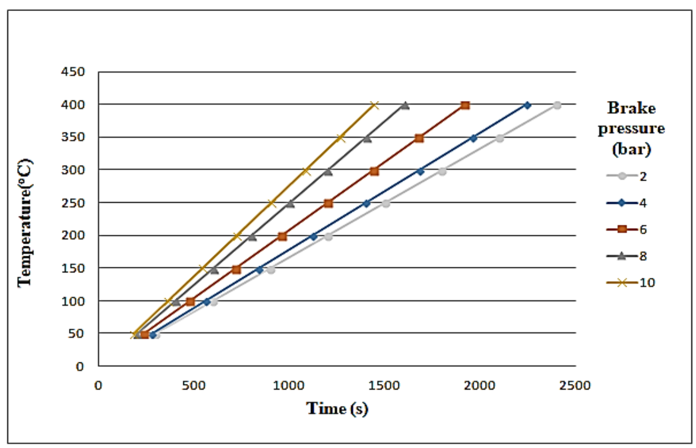



Fig. 5. Disc temperature change over time according to brake pressure.

As seen in Figure 5, it took approximately 22 minutes to reach the maximum temperature at a brake pressure of 10 bar. It was observed that when the brake pressure increased, the duration to get the maximum temperature decreased. Due to the reduction of brake pressures applied to the brake disc, it was noticed that the durations to reach the top temperature level were prolonged.

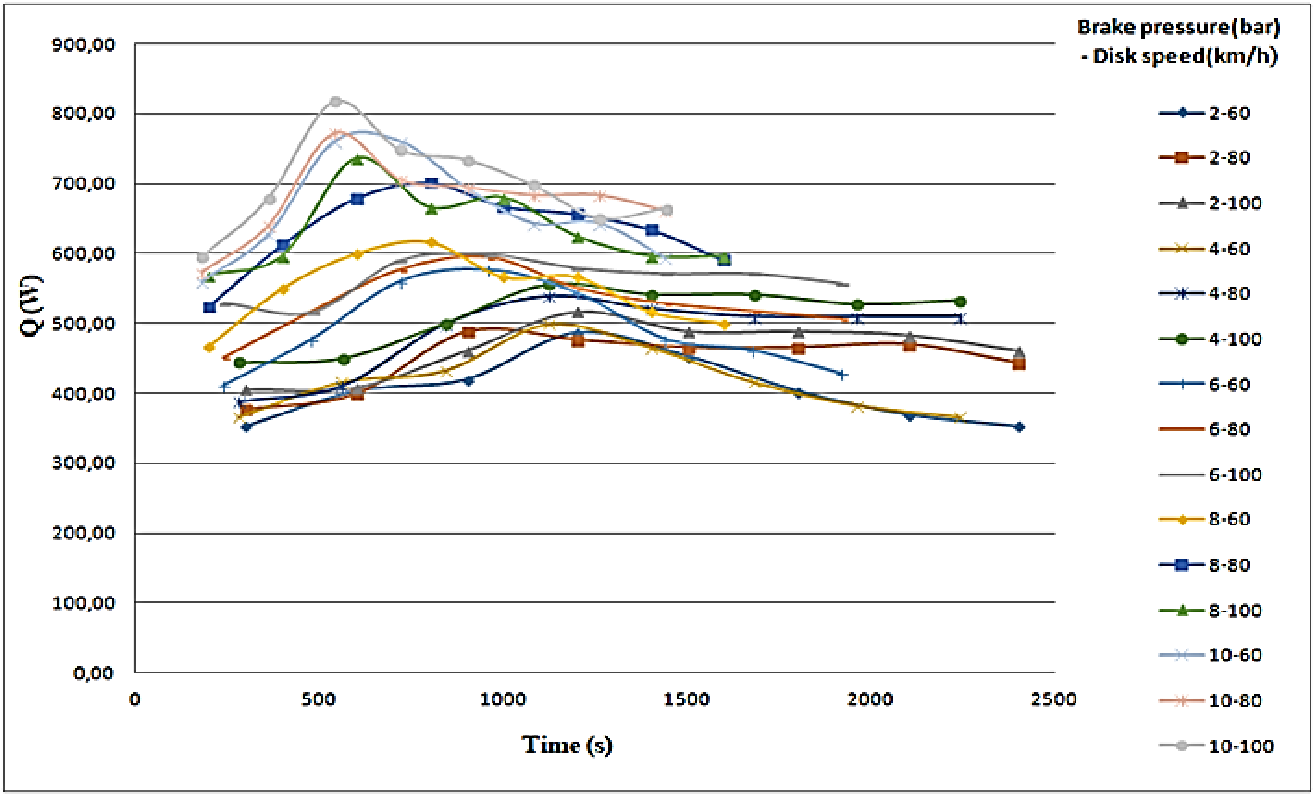



Fig. 6. Variation of heat loss over time depending on brake pressure and disc speed.

### *3.2. Findings of Energy Analysis*

Energy analyses were carried out according to the control volume examined in Figure 3(b), and heat losses during the operation were calculated. The results of the calculations are given in Figure 6.

As seen in Figure 6, the heat losses increased parallel to the temperature increase till around 200 °C. After specific temperature values, the heat losses decreased due to the slippage between the disc and the vehicle lining. Due to the extreme temperature, a glass film layer forms between the disc and the lining. This glass film layer formed increases the sliding speed between the disc and the lining. The braking force decreases as the friction coefficient decreases depending on the sliding speed increase [17].

The highest heat values were obtained by increasing the brake pressure at high disc speeds. At high temperatures, irregular wear occurs between the lining and the disc surface, and a glassy surface layer occurs between the lining and the disc. As a result, the lining starts to slip without holding to the disc surface.

The lowest heat values are obtained at low disc speeds when the brake pressure is low or at high disc speeds at low brake pressures due to the low friction coefficient between the disc and the lining. Therefore, the heat values are common.

### *3.3. Findings of Exergy Analysis*

Exergy analyses were carried out according to the control volume examined in Figure 3(b), and the exergy destructions that occurred during the study were calculated. The results of the calculations are given in Figure 7. Accordingly, the exergy destruction values appeared to be higher at higher disk speeds. This change can be due to the temperature values reaching maximum levels in a shorter time due to the friction between the disc and the lining at high speeds, and the temperature values increased in a long duration at low speeds. The most critical factor in exergy destruction is the temperature reaching high importance due to the friction between the disc and the lining. The reason why exergy destruction increased up to a specific value and then decreased was also the result of the decrease in heat losses due to the decrease in the friction coefficient due to the slip between disc and lining.

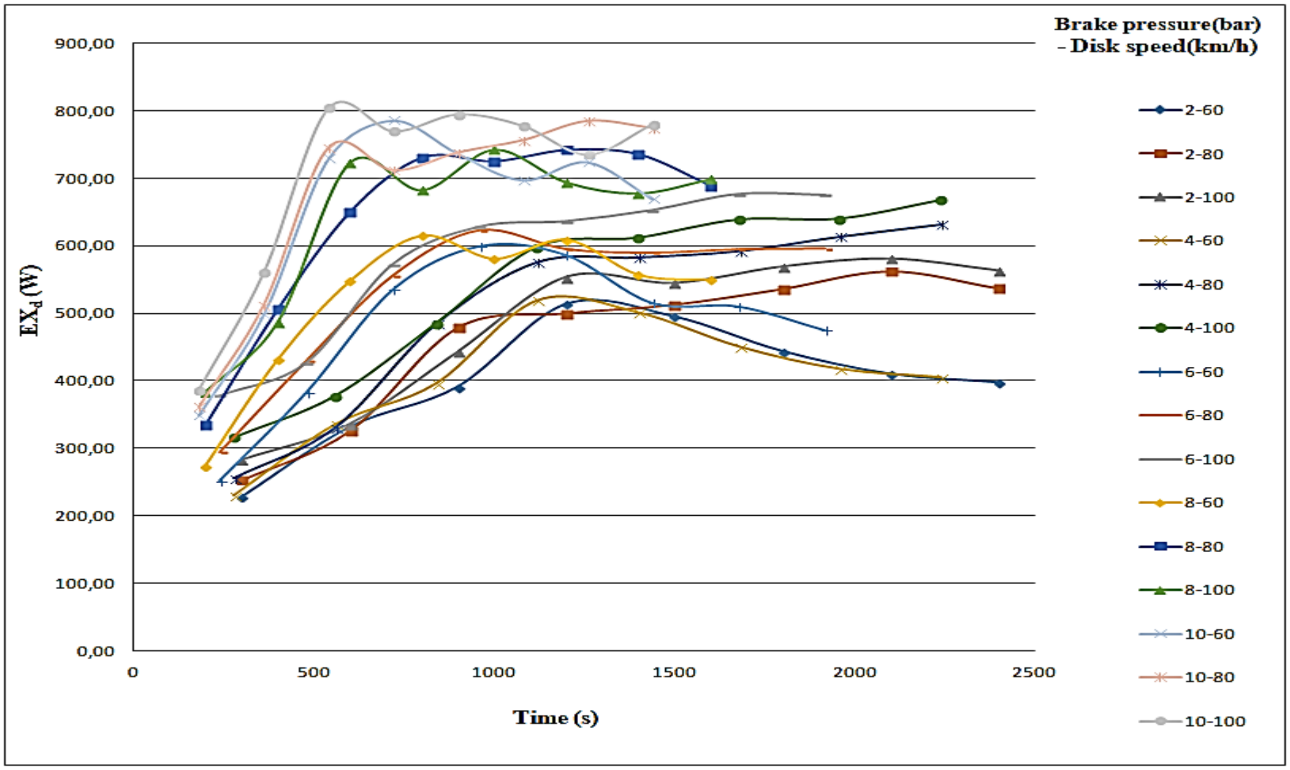



Fig. 7. Variation of time-dependent exergy destruction according to brake pressure and disc speed.

## 4. CONCLUSION

This research examined the effects of brake force change on time by evaluating the brake system from both energy and exergy perspectives. In real cases, braking times occur in short intervals, and maximum braking force values are at the temperature values of 200-250 ºC. When the lining or disc temperature reaches 315 °C or higher, it is seen that slipping begins on the disc system. This study determined that the ideal brake force values were around 200 ºC when continuous braking was applied in the brake test. The brake force decreased, and the braking process weakened at the temperature values of 250 ºC and above. Again, heat losses and the exergy destructions caused by this also increased due to high temperatures. Therefore, for an effective braking system, the temperature is one of the most critical parameters to be controlled. It may be suggested to cool the brake discs as it is the most effective solution for reducing these losses at the maximum possible operating temperatures. Related applications are currently available, usually on air-cooled brake discs. For this purpose, topology optimization such as holes, fins, ducts, hole-duct combination, and discs with four cooling surfaces may be applied to the discs.

## Nomenclature

Q Heat (J)
$\dot{Q}$ Heat power (W)
P Pressure (Pa)
W Work (W)
$W_P$ Brake force applied to stop the disc
$W_T$ Work of turning
$c_p$ Specific heat (J/kgK)
T Temperature (K)
$T_o$ Environmental temperature (K)
A Disc area ($m^2$)
V Vehicle speed (km/h)
$E_{in}$ Input energy of the system
$E_{Out}$ Output energy of the system
$Ex_{in}$ Exergy input rate of the system
$Ex_{out}$ Exergy output rate of the system
$Ex_d$ Exergy destruction rate of the system
$\mathcal{V}$ Lining volume ($m^3$)

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