EVALUATING THE EFFECTIVENESS OF MECHANICAL TRANSMISSION BASED ON THE ASSESSMENT OF ENERGY DISSIPATION

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Summary

The article discusses the relationship between the heat flow and the power supplied to a test object. Often, it is reasonable to say that the heat flow and power are correlated. Intuitively, one can assume that knowing the distribution of the heat flow in time permits to determine the power of a system. Such a statement is valid in some cases. In order to determine fault assumptions an experiment was carried out. The object of research was chosen so as to simplify the physical model of the experiment. The goal of the experiment was to study the heating power of systems consisting of tubes filled with water. The signal was recorded using thermistors and a thermal imaging camera. The analysis of the results shows that there is a strong relationship between the power supplied and temperature increase. Information on energy dissipation of a system is characterized by medium and small average error, thus, allows the evaluation of a machine's performance.

Keywords: machinery diagnostics, performance, thermography, thermistors

OCENA SPRAWNOŚCI PRZEKŁADNI MECHANICZNEJ W OPARCIU O OCENĘ DYSSYPACJI ENERGII

Streszczenie

W artykule omówiono związek pomiędzy przepływem ciepła, a mocą dostarczoną do badanego obiektu. Często zasadne jest twierdzenie, że przepływ ciepła i moc są ze sobą skorelowane. Intuicyjnie można przyjąć, że znając rozkład przepływu ciepła w czasie można wyznaczyć moc układu. Jest to stwierdzenie słuszne w niektórych przypadkach. Wykonany został eksperyment pozwalający określić błąd przyjętych założeń. Obiekt badań został dobrany tak by uprościć model fizyczny eksperymentu. Badana została moc grzewcza układów złożonych z rur wypełnionych wodą. Sygnał został zarejestrowany z wykorzystaniem termistorów i kamery termowizyjnej. Analiza otrzymanych wyników pokazała, że występuje silna relacja pomiędzy mocą doprowadzoną do układu a wzrostem temperatury. Informacja o dyssypacji energii układu cechuje się niewielkim błędem średnim i pozwala ocenić sprawność maszyny.

Słowa kluczowe: diagnostyka maszyn, sprawność, termowizja, termistory

1 INTRODUCTION

The performance of mechanical devices is the key parameter characterizing a machine's work. Technological development is associated with an increased processing of power as well as a more efficient use of energy. Today, rising energy costs result in the need to monitor the efficiency of devices. The efficiency is determined by the ratio of the power used by a device to the power supplied to it. The power output of a mechanical device can be measured directly or set by the difference between the power consumed and the power dissipated. In this case, performance can be determined using the following formulas:

$$\eta=\frac{N_2}{N_1}=\frac{N_1-\Delta N}{N_1}=1-\frac{\Delta N}{N_1} \qquad (1)$$

where:
η – mechanical efficiency of a bevel gear
N – power.

2 KNOWN METHODS OF MEASUREMENT OF MECHANICAL DEVICES PERFORMANCE WITH THE MEASUREMENT OF THEIR THERMODYNAMIC STATUS [1, 2]

The subject literature discusses two variants of tests allowing for determination of power loss through heat balance. Both concern the determination of the efficiency of mechanical transmissions. The methods rely on measuring the temperature of a transmission during operation with rated load. Then, using the heaters installed inside the transmission, one can determine the power that needs to be supplied to the transmission in order to obtain the same temperature or temperature field. During the test the transmission is idling, so that the sum of the heaters power and the power dissipated was equal to the idle power nominal energy losses during the transmission operation. The heaters in the transmission are arranged so as to obtain corresponding temperatures of the walls and the oil, as in normal operation.

In the first variant of the study the transmission is idling. The power is supplied using an engine of the power similar to the power of the idle. In this case, the power supplied by the engine (of known work characteristics and power consumption) is precisely determined. The power delivered by the idling engine is small when compared with the heaters heat output. Consequently, the initial error in assessing the power of the idle does not significantly affect the outcome of the research.

The second variant of the method is used mainly at factory posts, and it does not involve the replacement of the engine. The same engine is used at both rated and idle load. In this case, the designation of the power supplied by the engine is virtually impossible for the idling engine. The power supplied by the idling engine is determined by extrapolation of a function that determines the relationship between the power of the heater and transmission temperature.

Heat motion in the transmission can be expressed by the following formula:

$$Q=C(\Delta t)^{1,25} \quad (2)$$

where:

Q – heating rate,

Δt – difference in temperatures between the transmission and the environment,

C – fixed value determined empirically.

Total heat flow Q is composed of the idle heating intensity and the heaters heating intensity. On the basis of the temperature difference of the idle and the temperature difference during normal operation.

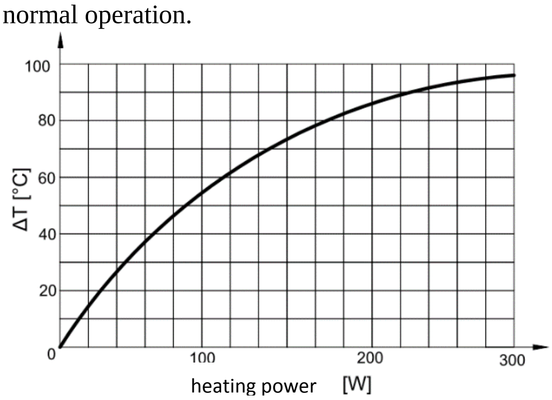

Fig. 1. Temperature dependence between a sample object and the heating power

3. TARGET USE AREA OF MACHINES PERFORMANCE TESTS WITH THE USE OF THERMODYNAMIC STATUS MEASUREMENT

Energy losses are inextricably linked with temperature increase. In addition to the heat losses, one can also mention other sources of energy dissipation in machines and devices. These are: the formation of magnetic fields, noise, chemical changes, wear of components, and the like. In case of some machines and devices, heat emission is the major source of unfavourable energy dissipation. In case of mechanical gears or bearings temperature measurement allows to estimate performance with little uncertainty.

4. THERMODYNAMIC BASES OF THE ADOPTED ASSUMPTIONS [3,4]

The adopted approach allows to evaluate the amount of heat energy dissipated by measuring the temperature. The method is based on the assumption that the amount of energy supplied to a body is proportional to temperature increase:

$$\Delta T = \frac{c \cdot m}{Q}, \quad (3)$$

where:

ΔT – temperature increase,

c – specific heat,

m – mass,

Q – supplied energy.

It should be noted that specific heat is a material constant and it may depend on temperature:

$$c(T) = \frac{1}{m}\left(\frac{dQ}{dT}\right). \quad (4)$$

The developed method assumes a breakdown of the model into ten identical operating distances, each of them having the same mass and heat capacity, and an associated temperature sensor. In case of the thermal imaging measurement, an operating distance is a single pixel of the section marked on the thermal image. Then, the quotient of specific heat, mass and temperature of a single operating distance is calculated. The adopted algorithm accomplishes the task in an identical way, by designating the average temperature. Then, the quotient of specific heat, mass and temperature of the entire system is calculated.

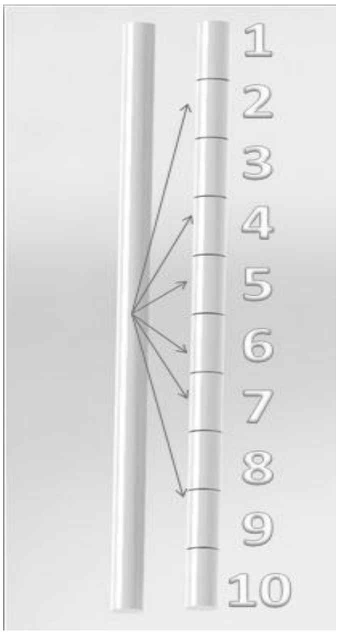

Fig. 2. Scheme of the concept of energy dissipation study

5. EXPERIMENTAL VERIFICATION

The proposed concept of machines performance tests would enable to accelerate and facilitate the process of assessing the suitability of a device. The assumptions were verified during a series of measurements. A series of experiments have been conducted to verify the size of the committed error in determining energy supplied to the system on the basis of temperature measurement. The designed test stand is composed of pipes filled with water.

Installed sensors measure the temperature at the point of contact with a pipe. The program allows to measure the changing resistance of a thermistor, and then determine the temperature according to a particular characteristic. Characteristics of the thermistors was determined by measuring the subsequent resistances and temperatures in steps of about 5 degrees Kelvin. The subsequent temperatures were determined using the UT71E thermometer by Uni-t with an accuracy of ±(1%+30). Then, a program was developed enabling to approximate the resulting measurements to form a linear relation. The function allows calculating the resistance of each thermistor into temperature. When calibrating NTC thermistors used for testing in a wide range of temperatures, the formula presented in the section describing thermistors should be used. For tests in a temperature range from 20 to 50 degrees the formula has been simplified into a linear form.

Inside the pipes there are heaters whose heat output is controlled by an autotransformer and a power analyzer. The temperature is measured on the pipes surface using equally spaced NTC thermistors. In the same time, measurement using a thermal imaging camera was carried out.

The stand (Fig. 3) includes:

1. Rigid rack
2. Copper pipe filled with water with embedded heater
3. Brass pipe filled with water with embedded heater
4. 10 NTC sensors spaced at equal intervals
5. Measurement card NI DAQCard-6062E
6. Computer
7. Power analyzer PowerAnalizer
8. Autotransformer
9. Thermal imaging camera

Data from the temperature measurement was used to determine a system's heat output. Then, the determined heating capacities have been verified with the actual heat output of the current indicated by the analyzer. During the analysis of the data a model was created enabling to determine the power using temperature measurements. Quotients of specific heat, mass of water and mass of the pipe (copper or brass) were added, thus, the system was treated as a whole. The algorithm employed consists of 6 steps:

1. Examination of temperature at 10 operating distances,
2. Determination of average temperature of a single measurement,
3. Calculation of a momentary energy of the system (the quotient of specific heat, mass and average temperature),
4. Calculation of energy increase ΔE,
5. Calculation of the quotient of energy increase ΔE in time, that is, the power,
6. Calculation of the average power.

The power (step 5) has been calculated in two ways. The first method, referred to as tn-1, involves the calculation of the quotient of energy increase and time between two subsequent measurements. The time between the subsequent measurements was 10 seconds. In the second method (referred to as tn-0), the power was calculated as the quotient of energy increase and time between the given measurements and the first measurement. A similar method was used to calculate the heat output using a thermal imaging camera. The difference in the measurement of a thermal analysis was based on the number of operating distances. Using a program for thermal analysis of the photographs, operating distances consisting of about 150 points were analyzed. Such an operating distance was used to calculate the average value.

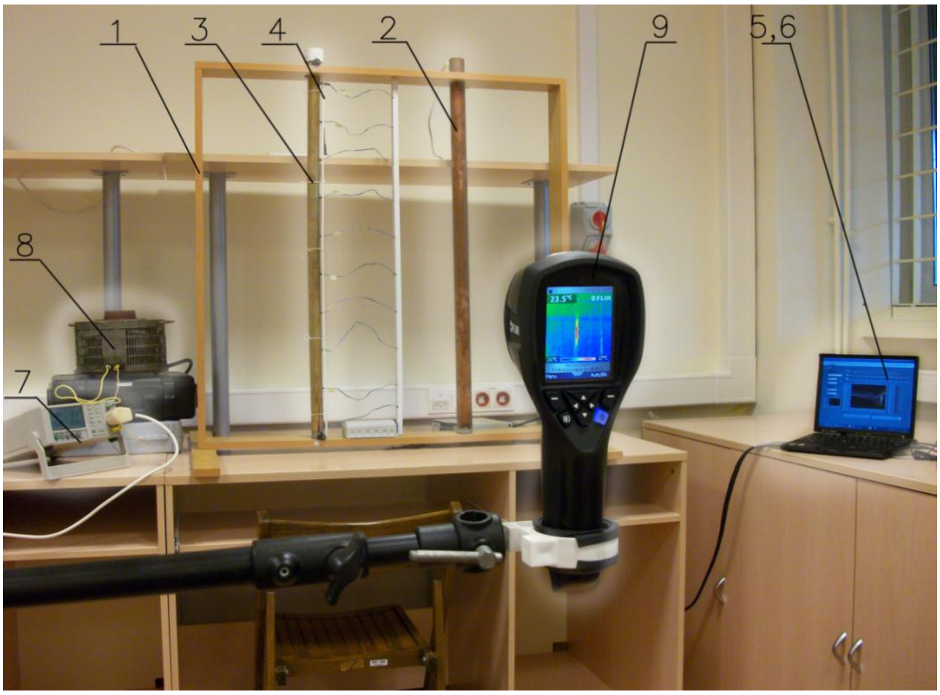

Fig. 3. Laboratory stand for determination of heat emission

6 RESULTS OF THE ANALYSIS

Ten experiments of heating the pipe with a known power were conducted. Both the copper and brass pipes were heated with a known power, of 21, 31, 41, 51, 61 W. The data collected from the measurements allows a comparison of the methods used to determine the power of a device. The exemplary power of the device was set using the power analyzer measurement. Changes in strength were held by adjusting the settings of the autotransformer. On the basis of each measurement, a power graph was plotted calculated at each time of the measurement. Figure 5 depicts powers obtained while heating the brass pipe with a power of 41 [W]. The research performed was characterized by error exceeding the system's thermal inertia. Data filtering eliminated thick mistakes that might have resulted from instability of the measurement system employed. The use of data filtering resulted in improved test results. To avoid such mistakes in further measurements changes were introduced in sampling frequency and time averaging of samples.

Parallel to the measurements carried out using NTC thermistors, measurements made with a thermal imaging camera were conducted. Captured images were edited using the FLIR QuickRaport program. The program enabled to change the emittance, so that temperatures were consistent with the measurement made with NTC thermistors. In spite of that, the measurements were characterized by a high relative error.

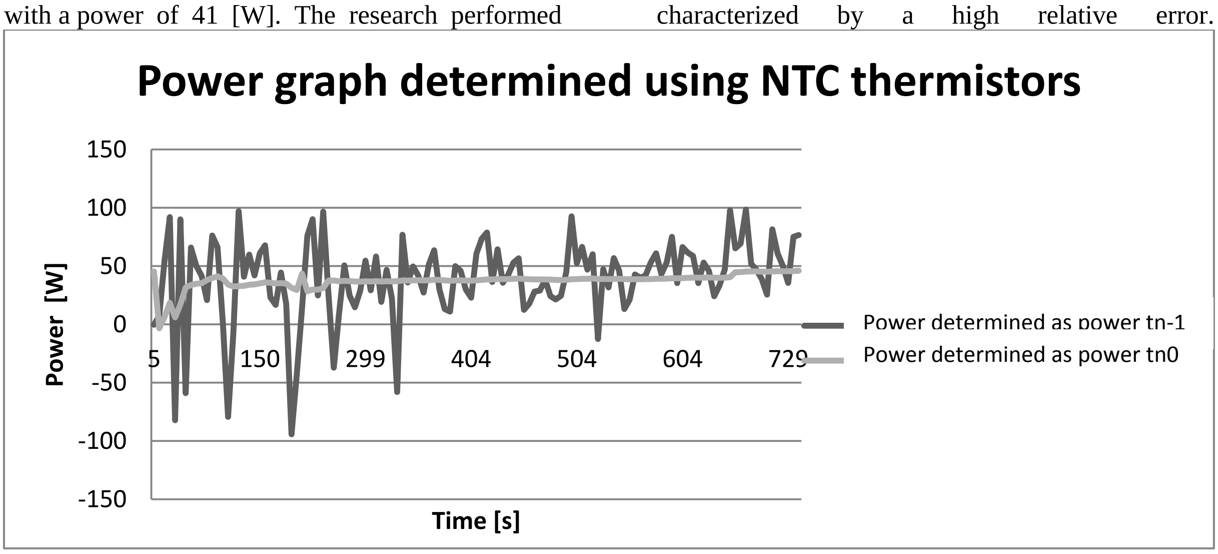

Fig. 5. Power graph determined using NTC thermistors with respect to the previous and the first measurement using the function of deleting data in excess of the agreed value; power of 41 [W]; brass pipe

Consequently, an error analysis of the tests was carried out. The smallest relative error was characteristic for measurements made using NTC thermistors in relation to the first measurement. The average relative error obtained during the measurement of that type is about 8.6%. A similar error was found in measurements made using the same method but calculated in relation to the previous measurement.

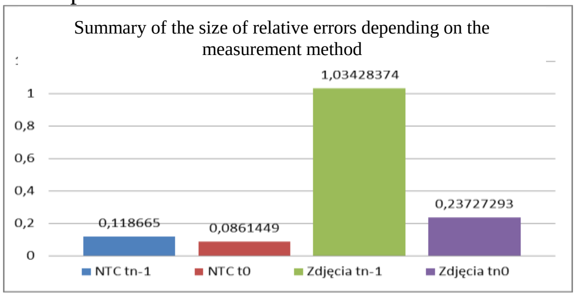

Fig.6. Summary of the size of relative errors depending on the measurement method

Figure 6 presenting a summary of the size of relative errors permits to state that the method of determining power in relation to the first measurement is sometimes characterized by a much larger error than when calculated in relation to the previous measurement. Powers calculated like that can be determined already after a few seconds of the measurement, and their values persist until the end of the measurement. Errors in measurements made with NTC thermistors may result from the adoption of the same characteristics for all the thermistors. A noticeable error, especially in measurements with NTC thermistors in relation to the previous measurement, are surges. They result from the instability of the measuring system used. This kind of error can arise, for example, from a bad contact of a thermistor with a test surface or poor grounding of a card. To prevent the generation of such data one should increase the time averaging of samples on a single measurement or extend the sampling time of a single measurement. Also signal filtering is possible.

The research and analysis of errors led to the development of the next version of the program for temperature measurement. The implementation of new features significantly reduced the size of the measurement noise and errors resulting from them.

Figure 7 illustrates the heating curves of measurements made on the stand with the copper pipe. In this case, the heating curves are best described with a straight line. The characteristic heating curve should be a logarithmic curve. The discrepancy may be due to the adoption of a linear characteristic of a thermistor or too small range of heating system, which proves the system's linear heating in a given temperature range.

The observation of errors arising during thermal imaging measurements also led to changes in the parameters of the study. Most measurements were made at a distance of three meters, which required bigger changes in parameters changing during the study than in case of measurements made at a closer distance. The last measurements, although in general they were characterized by a bigger relative error, did not require the same changes as in the preceding measurements. During the measurements the distance of measurement was reduced, the tripod was set to take pictures from the same perspective, and the stand was fitted with LEDs allowing for permanent identification of the measuring line in a program for thermal images analysis. Despite the reduction of subjective interventions, such as:

– framing of the shot,
– distance between the test object and the thermal imaging camera,
– points determining the line of measurement,

the relative error of thermal imaging measurements was greater than in measurements with the use of NTC thermistors.

7. CONCLUSIONS

The studies conducted using thermistor sensors were characterized by an average error of 10% in the case of heat output evaluation. In the majority of measurements the error resulted from a bad contact of the thermistor with the test surface. In the measurements in which this factor was eliminated the physical model employed permitted to evaluate the heat output with an error of about 1%.

At the second stage of the research work the same series of tests using thermal imaging measurements was carried out. In this case, the errors were significant and the data from the measurements had to be edited in the program for thermal images analysis. The emissivity ε has been changed, so that the temperature of thermal images corresponded to the temperatures measured with the thermistors, which ruled out the possibility of using the method independently. Despite the occurring measurement errors, the study of temperature changes dynamics may be used to estimate the amount of energy dissipated, and, thus, evaluate the efficiency of mechanical devices. Particular attention should be paid to the possibility of using the described method in the evaluation of bevel gears efficiency. Such an evaluation seems to be faster and less costly than other known methods of evaluation. In addition, the described algorithm can be used both during the control of the transmission at a factory stand as well as during the transmission operation at a production stand.

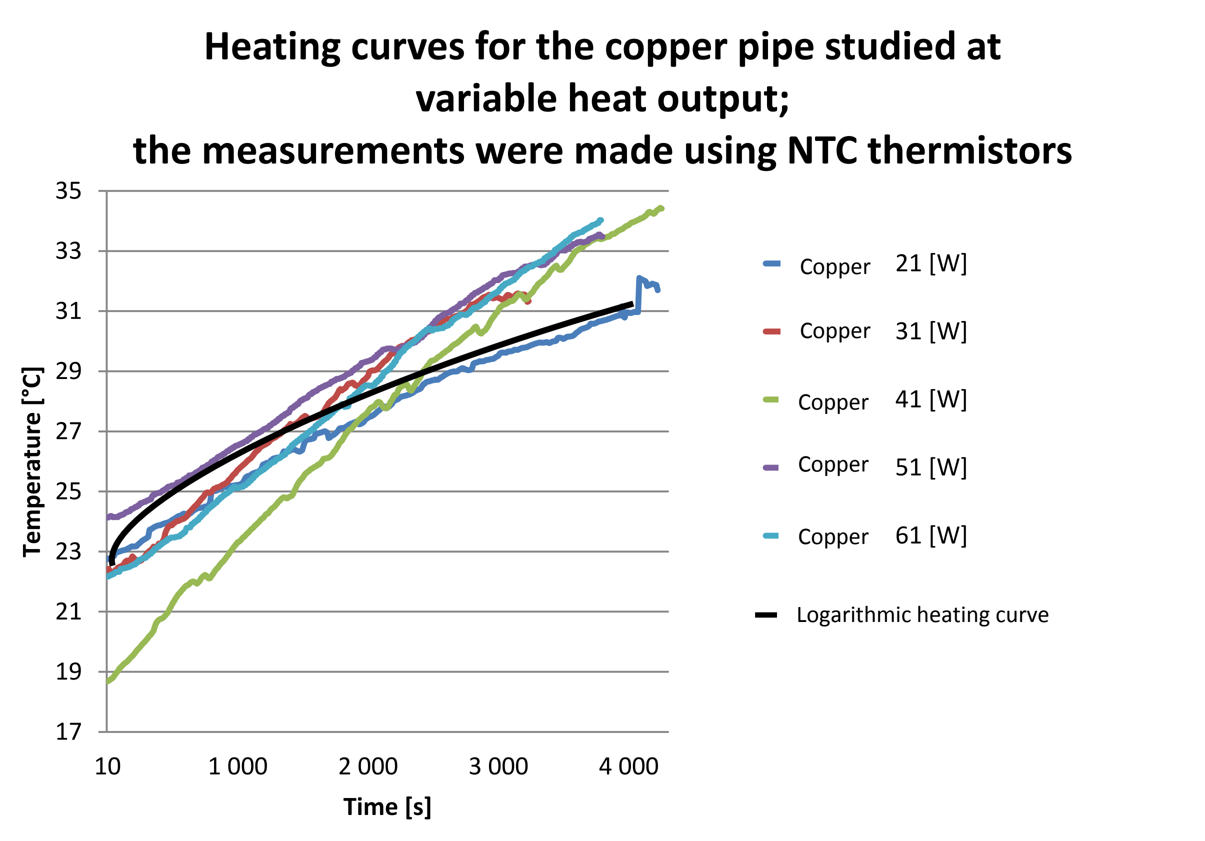

Fig. 7. Heating curves for the copper pipe studied at variable heat output; the measurements were made using NTC thermistors

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