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Nguyen Thuy Duong
Hanoi University of Science
and Technology, Hanoi,
Vietnam

Pham Van Hung
Hanoi University of Science
and Technology, Hanoi,
Vietnam

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EFFECT OF HUMID TROPICAL CLIMATE ON FRICTION CHARACTERISTIC OF PNEUMATIC CYLINDERS

Nguyen Thuy Duong*, Pham Van Hung
Hanoi University of Science and Technology, Hanoi, Vietnam

The pneumatic cylinder is influenced by many various factors at work, including the climate environment. The climatic environment consists of two characteristic factors as temperature (T) and relative humidity (RH), which change according to seasons and different geographical regions. Therefore, changing the climate characteristic factors will affect the friction characteristic of pneumatic cylinders when operating at different speeds. This article presents empirical research on the simultaneous effects of temperature and relative humidity of the environment with the humid tropical climate in Vietnam on the pneumatic cylinder's friction properties. According to experimental planning, the studies were conducted on industrial pneumatic cylinders with two input factors: the temperature of 15°C, 32°C and 49°C and relative humidity of 51%, 75% and 99%, with velocities of 30, 50 and 100 mm/s. The results show that the static friction force and dynamic friction decrease when T, RH increases, and the influence of air relative humidity on friction force is more significant than temperature. The experiment also gives an empirical regression equation on the relationship of friction in the pneumatic cylinder, depending on the two factors of temperature and relative humidity of the humid tropical climate in Vietnam with velocities of 30, 50 and 100 mm/s.

Key words: humid tropical climate, friction force, friction characteristic, pneumatic cylinders

INTRODUCTION

Vietnam is located in a tropical monsoon climate with an average seasonal relative humidity (RH) ranging from ~51% to ~99% and average temperature (T) ranging from ~15°C to ~49°C. In climatic environments, the air relative humidity and temperature are important factors that directly affect the tribology characteristic of friction structures in the absence of critical lubricants or boundary lubrication. Nguyen Anh Tuan et al. studied the effects of Vietnam's climate with relative humidity changes on the wear of cast iron and steel materials. The results showed that the amount of wear increases rapidly with increasing relative humidity [1]. Nguyen Anh Tuan and Pham Van Hung studied the effects of Vietnam's humid tropical climate on the wear of cast iron materials [2]. The studies have been conducted when changing air temperature and relative humidity. The results show that at low RH and high temperature, the wear coefficient is low and vice versa, the wear coefficient is high when the RH is high, and T is low. The studies [3-8] have shown that the friction of material pairs is significantly influenced by air humidity, which decreases with increasing relative humidity. The climatic environment characteristics (RH, T) also directly affect the friction of the pneumatic cylinder. It is a cause of unstable movement of the pneumatic cylinder. This friction occurs between the washers - piston rod and washer - cylinder. Therefore, to improve the motion quality of pneumatic cylinders, it is necessary to study the behaviour of friction in different working conditions, including the climatic factors. T.Raparelli [9] showed that when pressure does not change the relationship of friction in pneumatic cylinders and velocity which is an exponential function and friction decreases when the pis-

ton is lubricated. The friction of the pneumatic cylinder during the initial displacement phase mainly depends on displacement and in the complete sliding phase mainly depends on speed [10]. Xuan Bo Tran and Hideki Yanada have shown that friction changes linearly with speed at high-speed range [11] and friction in the displacement phase changes nonlinearly with pressure [12]. In addition, [13] has determined that the stick-slip phenomenon in a pneumatic cylinder occurs at the velocity of 0.010 m/s. However, a little research on the effects of climate factors has been carried out. Only a few studies deal with individual humidity or temperature factors to friction in pneumatic cylinders. Niko Heraković [14] has shown that friction force is significantly influenced by pressure and temperature. In the temperature range of 20°C–22°C, the friction force decreases on average from 2 to 2.5 N for a temperature increment 1°C. Takahiro KOSAKI et al. have also shown that the pneumatic cylinder's friction force decreases and depends on the speed at higher speeds [15]. The researches [16,17] have shown that friction force in pneumatic cylinders decreases as RH increases from 51% to 99% while also defining friction force as a function of RH and velocity. Pham Van Hung [18] studied the effect of air temperature on friction in pneumatic cylinders. The results show that friction is reduced by 10-18% when the temperature increases from 15°C to 49°C and the change in static friction is 1.2 times greater than the dynamic friction force. Thus, the above studies mainly focus on the behavior of friction in pneumatic cylinders with the changing factors such as p, v, vibration, and without lubrication; a few studies mentioned the influence of temperature and relative humidity. How-

*duong.nguyenthuy@hust.edu.vn

ever, the study on the simultaneous effects of two factor RH and T of climate on the pneumatic cylinder's friction is rarely mentioned.

This paper presents the effects of humid tropical climate Vietnam with two characteristic factors, RH and T, on the friction properties in pneumatic cylinders at different speeds.

METHOD EXPERIMENT AND APPARATUS

Experimental design

To study the simultaneous effects of both the characteristic climate parameters, RH and T, on the pneumatic cylinders' friction properties, we conducted the experimental planning with two inputs. The two input factors, RH and T, have a range of varieties suitable for the humid monsoon tropical characteristics of Vietnam, including:

- RH changing in a range of 51÷99%;
- T changing in a range of 15÷49°C.

The output function is the friction properties of pneumatic cylinders, including static friction force (F_s) and dynamic friction (F_D) determined at different displacement speeds. We implemented full experimental planning of quadratic type 2k [19] at each survey speed. The orthogonal second order design specifies the number of experiments N as follows Eq. (1):

$$N=2^k+2k+n_0=9 \tag{1}$$

where

- k – Number of inputs;
- 2^k - Number of tests of the norm;
- 2k - Number of extensive experiments;
- n_0 – Number of experiments in the center.

The input parameters of the research are shown in Table 1.

Table 1: Input parameters of the research

Parameters	Coded values		
X_1	-1	0	+1
X_1 °C	15	32	49
X_2 %	51	75	99

Table 2: An experimental array of the research

No	Real variable		Encoding variable					F_i (N)
	X_1	X_2	x_0	x_1	x_2	x'_1	x'_2	
1	15	51	+	-	-	1/3	1/3	F1
2	49	51	+	+	-	1/3	1/3	F2
3	15	99	+	-	+	1/3	1/3	F3
4	49	99	+	+	+	1/3	1/3	F4
5	15	75	+	-	0	1/3	-2/3	F5
6	49	75	+	+	0	1/3	-2/3	F6
7	32	51	+	0	-	-2/3	1/3	F7
8	32	99	+	0	+	-2/3	1/3	F8
9	32	75	+	0	0	-2/3	-2/3	F9

Where: X_1 – Temperature
 X_2 – Relative humidity

The tests are carried out under conditions without external lubrication on the piston, and the pressure in the pneumatic cylinder is equal to the atmospheric pressure. The reciprocating motion of the pneumatic cylinder is driven from the outside.

The experimental array for orthogonal second order design was built according to Table 2 [19].

Where: x_1, x_2, \dots are dimensionless encoding values of X_1, X_2, \dots ;
 x'_1, x'_2, \dots are sub variables of x_1, x_2, \dots ;
 F_i is output function.

Experiment and apparatus

The experimental apparatus is shown in Figure 1.

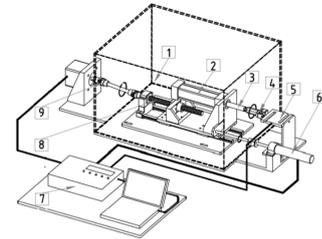


Figure 1: Schematic of the experimental apparatus

- 1-Environment chamber, 2-Pneumatic cylinder,
- 3-Piston rod, 4-Spherical joint, 5-Load cell,
- 6-Displacement transducer, 7-Data system,
- 8-Ball screw, 9 – Coupling.

The piston rod is fixed, while the cylinder can move relative to the piston. The motion of the cylinder is driven with velocities precisely controlled by a servo-driven motor through a ball-screw transmission. The equipment system is located in the BKNA1 environment chamber with a RH can be controlled in a range of 51÷99%±2% and T can be controlled in a range of 15÷49°C±1°C. Using a displacement transducer DTH-A with an accuracy of less than 0.1% RO to measure the cylinder's displacement. The friction force F_s and F_D of the pneumatic cylinder is measured by a load cell with an accuracy of

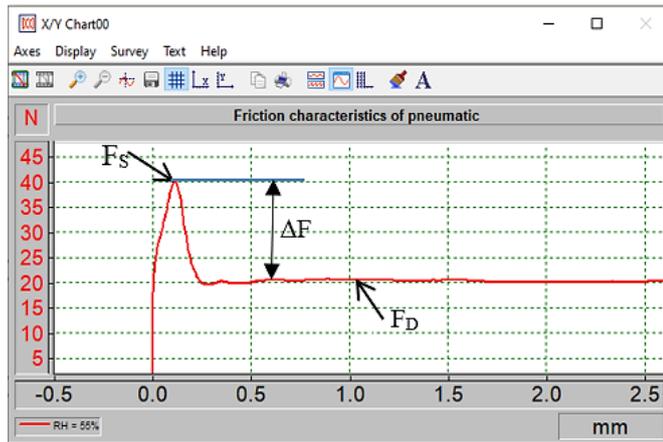


Figure 2: Friction behavior of pneumatic cylinder

less than 0.02% F_s , which is set between the piston rod via a spherical joint and a fixed plate. The displacement and the friction force are conducted, processed, and displayed on the computer screen through the software DasyLab 11.0. The screen interface shows the results of measuring friction characteristics, including the static friction force F_s and dynamic friction force F_D according to displacement stroke showed in Fig 2.

The friction force is a function of displacement [20], including Stage I-preliminary displacement; Stage II - breakaway; and Stage III - sliding. After the preliminary displacement stage, there is a sudden decrease from the maximum force of static friction (F_s) to dynamic friction force (F_D). The detail experimental conditions are listed in Table 3.

Table 3: Experimental conditions

No	Parameters	Experimental conditions
1	Pneumatic cylinder, STNC	D=50mm, d=20mm, h=150mm
2	Velocity (v)	30,50,100mm/s
3	Humidity (RH)	51%, 75%, 99%
4	Temperature (T)	15°C, 32°C, 49°C
5	Surface conditions	No lubrication
6	Pressure	Atmosphere

RESULTS AND DISCUSSIONS

To evaluate the effect of humidity and air temperature on friction properties (F_s , F_D) of a pneumatic cylinder,

we conducted the friction test as follows: Set the relative humidity mode to 51%, the temperature changes as 15°C, 32°C, and 49°C, respectively and study friction characteristics at speeds of 30mm/s, 50mm/s, 100mm/s, respectively. Similarly, other experiments conducted at a relative humidity of 75% and 99% with the temperature changes as 15°C, 32°C, and 49°C, respectively. The data of friction are shown in Table 4.

Static friction

Base on the experimental data shown in Tables 4, the mathematical equation of static friction F_s at different speed is shown in Eqs. (2, 3, 4), as follows:

$$F_{S(30mm/s)} = 14.8901 - 0.0827 \cdot T + 0.1358 \cdot RH - 0.0013 \cdot RH^2 \quad (2)$$

$$F_{S(50mm/s)} = 17.3885 - 0.0781 \cdot T + 0.1062 \cdot RH - 0.0010 \cdot RH^2 \quad (3)$$

$$F_{S(100mm/s)} = 21.9854 - 0.0792 \cdot T + 0.1245 \cdot RH - 0.0012 \cdot RH^2 \quad (4)$$

The experimental equation (2,3,4) shows that the pneumatic cylinder's static friction force is significantly influenced by the relative humidity and the air temperature, and it decreases as T and RH increase. However, the decrease in F_s with RH is greater than that with T, which is shown in a second-order nonlinear relationship with RH. It can be explained by the appearance of a moisture film on the friction surface. It plays as the boundary lubrication on the friction surface. This boundary lubrication layer is highly dependent on the change in the moisture film thickness that forms on the surface as the RH and T of the air vary. When T and RH are high, the moisture film produces a more significant boundary lubrication effect than when T and RH are low. Simultaneous dependence of friction force F_s on two factors RH and T, at the study speeds, is also shown in figure 3.

Figure 3a shows that the friction force F_s has the maximum value in the humid thermal complex (T=15°C, RH=51%) at all 3 speeds. When the temperature and relative humidity increase, the friction force decreases and reaches the smallest value in the region T=49°C and RH=99%. Figure 3b shows RH and T's simultaneous effect on the friction force F_s through contour lines at all 3 speeds. The density of the contour lines represents the influence of the two related parameters, RH and T. When temperature and humidity increase, the contour lines lie closer together, meaning that the higher the temperature and humidity, the stronger the effects of temperature and

Table 4: The data of static friction and dynamic friction

N ₀ experimental		1	2	3	4	5	6	7	8	9
v (mm/s)	F(N)									
30	F_s	17.41	14.41	14.39	11.61	16.85	13.85	15.61	13.27	14.8
	F_D	13.8	11.61	10.79	8.36	12.9	11.28	12.9	9.93	11.84
50	F_s	19.05	16.22	16.41	13.85	18.56	15.75	17.57	15.38	15.75
	F_D	16.52	13.31	13.37	10.47	15.52	12.71	14.89	11.88	12.71
100	F_s	24.2	21.26	21.18	18.75	23.7	20.75	22.52	20.23	21.68
	F_D	22.12	19.5	19.78	116.3	21.58	18.73	20.9	17.8	19.85

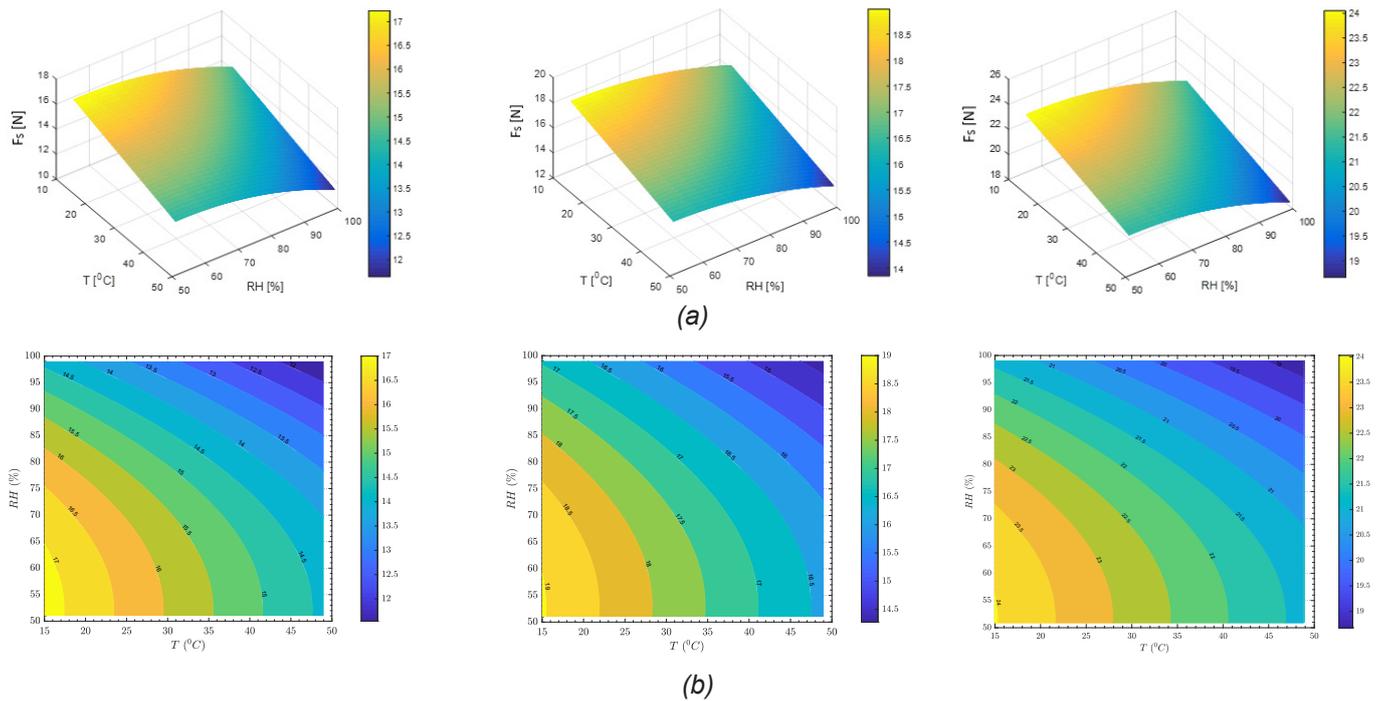


Figure 3: The scheme of the variation of the F_s according to T and RH at several speeds

humidity variation on F_s . This suggests an inverse phenomenon that reduces the effect of the changing of T and RH on the F_s in the lower regimes. At the same value of friction force F_s - contour line, we can choose many different sets of RH and T values. Thus, based on the chart in Figure 3b, the phenomena, discussions on the mechanism of formation and transformation of the F_s can draw the following comments:

The effects of temperature and relative humidity of the air environment on F_s are obvious and complex; The effect on relative humidity on F_s is stronger than that at high temperature, meaning that the effects of relative humidity are 'amplified' at high temperature. The friction force F_s can be controlled at specific speeds by selecting the pairs of RH and T pairs on suitable contour lines. This static friction force F_s should be considered in source problems when starting.

Dynamic friction

From the experimental data shown in Table 4, the mathematical equation of dynamic friction F_D at different speeds is shown in Eqs. (5,6,7) as follows:

$$F_{D(30\text{mm/s})} = 10.7477 - 0.0594 \cdot T + 0.1478 \cdot RH - 0.0014 \cdot RH^2 \quad (5)$$

$$F_{D(50\text{mm/s})} = 15.6835 - 0.08495 \cdot T + 0.0911 \cdot RH - 0.001 \cdot RH^2 \quad (6)$$

$$F_{D(100\text{mm/s})} = 20.9437 - 0.0852 \cdot T + 0.110 \cdot RH - 0.0013 \cdot RH^2 \quad (7)$$

The experimental equation (5,6,7) shows that the dynamic friction force F_D of the pneumatic cylinder is significantly influenced by the relative humidity and the air temperature. The law of variation of dynamic friction depends on the temperature - humidity as the static friction. However, the complete sliding regime is much larger than the preliminary displacement, the boundary lubrication

effect appears and transitions to hydrodynamic lubrication is faster, so the dynamic friction force value F_D with T and RH is usually smaller. At higher speed will cause a stronger hydrodynamic effect and a lower frictional force. The dependence of the friction force F_D in the pneumatic cylinder on the humid tropical climate is due to its nature seal material and boundary lubrication - hydrodynamic of the moisture film formed on the surface of the piston rod. The scheme of the variation of the dynamic friction force according to the humidity and the air temperature is shown in Figure 4.

Figure 4a also shows that the friction force F_D is significantly influenced by the heat-moisture environment in Vietnam. In the heat-moisture complex area ($T=15^\circ\text{C}$, $RH=51\%$), the friction force has the maximum value. When the temperature and relative humidity increases, friction force decreases and reaches the smallest value in the region ($T=49^\circ\text{C}$, $RH=99\%$). Figure 4b shows the simultaneous effect of RH and T on friction force F_D . As with F_s , Figure 4b shows that the contour lines' density is closer together as temperature and humidity increase. This shows the greater impact of the change levels T and RH on F_D . At high speed, the reduction of contour density shows a reduction of frictional force F_D , and it has a small value due to the hydrodynamic lubrication effect formed with the moisture film.

CONCLUSION

The influence of humid tropical climate in Vietnam with characteristic factors such as RH and T on the friction behavior of pneumatic cylinders has been studied. Some conclusions can be drawn as follows:

1. The two characteristic factors of the humid monsoon tropical climate RH and T have a significant and

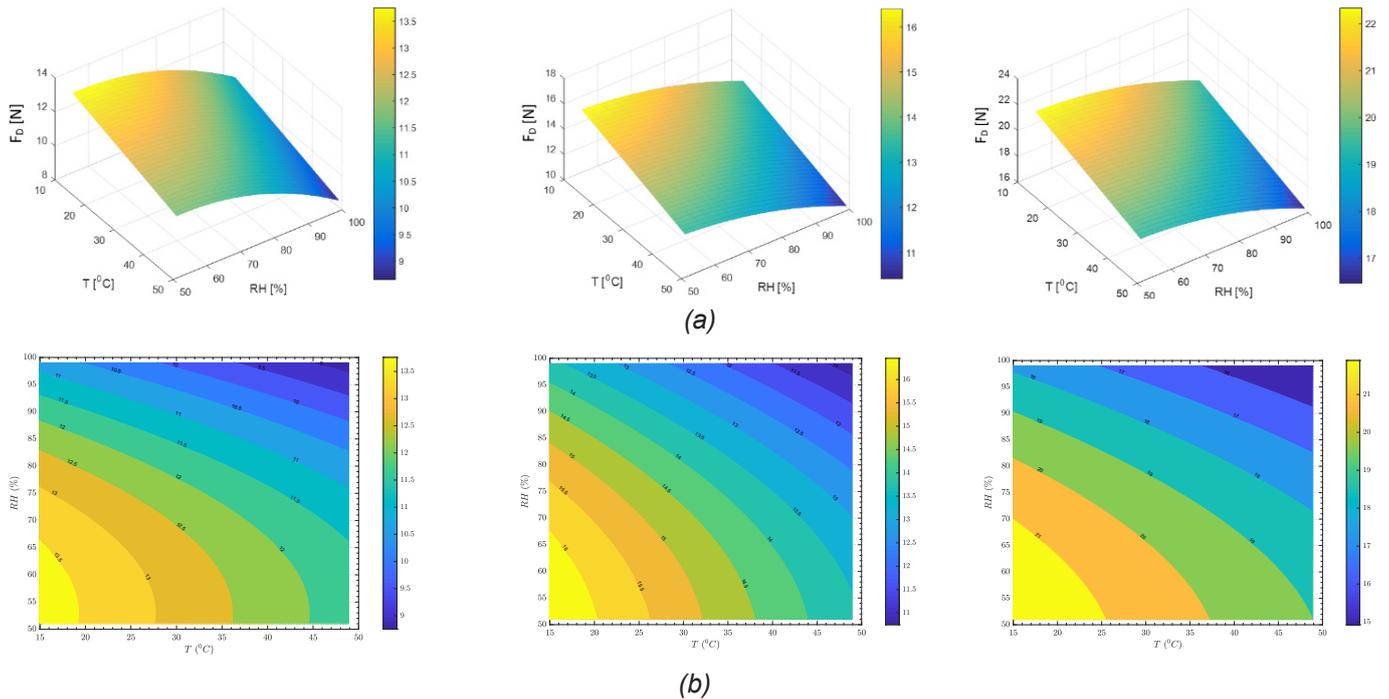


Figure 4: The scheme of the variation of the F_D according to T and RH at several speeds

- complex influence on the pneumatic cylinder's static friction force and dynamic friction. The minimum friction force exists in the region with low RH, T and vice versa.
- Determining the laws of variation of friction characteristics (F_s and F_D) simultaneously depend on the change of RH and T. These rules can be applied to speed and precise position control of the pneumatic cylinder.
 - The study has shown the contour lines of friction force as a "Friction map" when the temperature - humidity changes. It allows an easy determination of each element's influence in the temperature-humidity pair and the couple's reciprocal effect on friction characteristics. This allows choosing the suitable RH-T pairs to control the friction value as required.

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