Assessing the Opportunity to Use the Infrared Thermography Method for Predictive Maintenance of Hydrostatic Pumps

Alexandru-Daniel Marinescu, Corneliu Cristescu, Teodor Costinel Popescu
Special Equipments Department, Hydraulics and Pneumatics Research Institute INOE 2000-IHP,
Bucharest, Romania
marinescu.ihp@fluidas.ro

Carmen-Anca Safta
Power Engineering Faculty
University Politehnica of Bucharest
Bucharest, Romania
safta.carmenanca@gmail.com

***Abstract*—In the operation of hydrostatic drive systems, the maintenance has an important role to maintain the designed parameters and efficiency. The paper presents an experimental approach regarding the possibility to use the infrared thermography method in the behavioral prediction of the hydrostatic drive systems. To simulate the malfunction of a hydraulic gear pump a test bench was designed and built so that three steps of pressure were considered and different operating modes by using a variable throttle on the pump's suction. The pump temperature was measured with an infrared thermal imaging camera, and an infrared thermometer. The results were compared between the two methods of pump monitoring using non-contact temperature measurements. The conclusion is that infrared thermography can be used as a qualitative method, and by increasing the accuracy of measurements it can also be used as a quantitative method in the predictive evaluation of the behavior of hydraulic equipment.**

***Index Terms*--hydraulic drives, infrared imaging, predictive maintenance, measurement errors**

I. Introduction

Maintenance is "still a challenge" in engineering equipment and as an "integral part of the production strategy" is depending on the equipment complexity, human factor, product quality and profitability [1]. Maintenance of hydraulic systems is based on a preventive maintenance which is a planned program based on the operating mode of each hydraulic device so that to maximize the device lifetime and to reduce the hydraulic system failure. The predictive maintenance is a maintenance method in which measurements and signal processing methods are able to accurately diagnose the equipment behavior during operation mode [1]. For hydraulic system the oil analysis is a predictive maintenance method. Vibration analysis and thermography are predictive maintenance techniques that can be used to monitor the condition of an engineering system [2]. The goal of the paper is to use the infrared thermography in hydrostatic drives as a method of predictive maintenance.

All objects with the temperature above absolute zero emit energy within the infrared band which provides the basis of infrared imaging or thermography [2], [3]. As an invisible portion of the electromagnetic spectrum the wavelength of infrared is between 0.78 μm and 1000μm [3]. Infrared light can be focused, reflected or absorbed like visible light.

Based on the fact that the intensity of infrared radiation from an object is a function of its surface temperature, the thermal cameras can record the temperature of various objects and assign each temperature to a shade of a color in the visible spectrum. Cold temperatures will have cold colors (violet, blue, green) and worm temperatures will have worm colors (yellow, orange red). Inside of a thermal imaging cameras the infrared radiation is detected and captured by microbolometers which are recording the temperature and assign the pixel to an appropriate color. Each pixel has a microbolometer. A thermal image of the system, Figure 1, is obtained and a temperature scale help us to know the temperatures in different points of the system [3], [4].

Using infrared cameras more information is obtained then infrared thermometers. Infrared cameras can give a structural deficiencies image and temperatures on any point of the structure's surface; infrared thermometers measure only the temperature from a distance. Each method is a non-contact method to measure the temperature. Infrared thermometers use a lens to focus infrared light from an object onto a thermopile (the detector) which absorbs the infrared light and turns into heat. The heat is turned into an electric signal transformed then into temperature [3], [4].

Three types of thermal energy can be detected from any object but only energy emitted from the object is important in predictive maintenance which propose the infrared thermal imaging as method of work. Energy reflected from the object and energy transmitted by the object are sources of errors and uncertaineties in infrared temperature technique [5]-[7]. Object emissivity (ε), incorrect evaluation of ambient

978-1-5386-3943-6/17/$31.00 ©2017 IEEE

temperature (T_0) or atmospheric temperature (T_{atm}), relative humidity (RH), the distance between the object and infrared cameras (d), incorrect evaluation of ambient radiation direct or reflected by the object, are some of the errors that can appear in the measurement method [5], [7]. Object emissivity coefficient of infrared cameras (or even infrared thermometer) are important sources of errors.

The experimental approach of using the infrared thermal imaging cameras as tool in the predictive maintenance of a hydraulic gear pump is described in Section II. Temperature of the gear pump was measured with an infrared thermometer (IT) and an infrared thermal imaging cameras (IC). Results and discussines are presented in Sections III and IV.

II. STAND DESCRIPTION AND EXPERIMENTAL PROCEDURE

The goal of the paper is to demonstrate that infrared thermography method is efficient in the maintenance prediction of hydrostatic drives. For this, different operating scenarios are experimental simulated in the simplest hydraulic circuit with a gear pump. The pump is working at different pressures and flow rates obtained by changing the flow aria in the hydraulic circuit as though different failure events are happening. The result of a malfunction in a hydraulic circuit can be the increase of the temperature in the hydraulic drive system or noises and vibrations.

A test bench designed and built at INOE 2000-IHP Bucharest, it is used to simulate various operating modes of a hydrostatic gear pump. The hydraulic scheme of the test bench is presented in Fig. 1. The hydrostatic gear pump (HP) works in different suction conditions changed with a variable throttle (ST) placed on the suction pipe of the gear pump. Even cavitational operation condition can be simulated if the flow throttle area is less enough. Different oil pressure steps are changed in the hydraulic system using the variable throttle (RT) mounted on the discharge circuit of the pump. The pressure limiting valve (noted as PRV in the scheme) is an over-loaded protector in the hydraulic scheme and the oil pressure steps in the circuit are measured with the gauge pressure (G) parallel mounted with (RT) and (PRV) in the discharge circuit of the pump. The other devices in the hydraulic scheme are named in Figure 1.

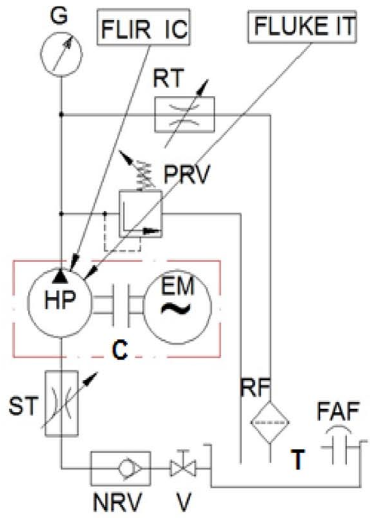
The hydraulic pump is operating on three steps of pressure (50bar, 75bar, 100bar) which are set with the variable discharge throttle RT. For each pressure step the area of the suction circuit on hydraulic pump is changed becoming smaller and smaller so that hydraulic oil temperature is heated in time. The increase temperature is measured on different moments of time. Temperature variations are measured even in the case of pump operation without variable throttle ST on the suction circuit, when flow area is large opened.

Two operating modes are considered: with throttle ST and without throttle ST, and temperature increasing in time is measured and monitoring in each step of prescribed pressure.

The sequence of phases in the experimental procedure in each operating modes are:

- start the gear pump;
- adjust the desired pressure step, by actuating the variable throttle RT;
- verify the suction circuit to have the throttle ST open;
- measure the gear pump temperature, at zero-time experiment, by using FLIR IC infrared thermal imaging camera and FLUKE IT infrared thermometer;
- reading the temperature of the environment;
- maintain the operating mode and measure from 10 to 10 minutes the pump temperature using the two methods mentioned above;
- stop the pump if the pump temperature is getting 80°C;
- repeat the procedure for each pressure step and monitor the temperature.

The same sequences of the procedure have been involved if a pump malfunction is simulated by closing the suction throttle ST, after setting the working pressure by actuating RT.



a)

b)

c)

Figure 1. Test bench. a) Hydraulic scheme: HP-hydraulic pump; EM-asincron electric motor; C-coupling; T-tank; FAF-filling air filter; RF-return filter; V-valve; NRV non return valve; ST-suction throttle; RT-discharge throttle; G-pressure gauge; PRV-pressure limiting valve; FLUKE IT-infrared thermometer; FLIR IC- infrared thermal imaging camera; b) Picture of the test bench; c) Test bench thermogram.

Non-contact measurements of the temperatures have been used the FLUKE 66 and FLIR InfraCam.

FLUKE 66 is an infrared thermometer with a measuring range of -32°C to 600°C and ±1% measurement accuracy above 23°C the ambient operating temperature. The emissivity is adjustable from 0.1 up to 1.00 and the infrared spectral response is 8µm to 14 µm [8].

FLIR InfraCam is an infrared thermal imaging cameras with 120x120 pixels resolution, the measuring range of -20°C to +250°C and the accuracy of ±2°C or ±2% of reading for ambient temperature 10°C to 35°C and object temperature above +0°C. The emissivity is adjustable 0.1 to 1.0 and infrared thermal response is 7.5µm to 13 µm [9].

III. RESULTS

For each operating mode (without throttle and with throttle, ST) and each pressure step (50bar, 75bar, 100bar) the gear pump temperature was measured using the non-contact infrared thermometer and infrared imaging camera method. The measurements are listed in Table I and Table II. The tables are structured according to the operating mode, pressure, time and type of temperature devices.

TABLE I. PUMP TEMPERATURE MEASUREMENTS WITHOUT THROTTLE

Pressure (bar)	Time (min)	Temperature (°C)		T_{ab_noST} (°C)	Error $\varepsilon_{T_{ab\_noST}}$ (%)
		FLUKE T_{IT}	FLIR T_{IC}		
50	0	28.90	29.2	-0,30	-1,027
	10	44.20	45.6	-1,40	-3,070
	20	51.40	51.7	-0,30	-0,580
	30	56.60	58.1	-1,50	-2,582
	40	61.50	62.9	-1,40	-2,226
	50	65.90	67.8	-1,40	-2,080
	60	70.70	71.3	-1,10	-1,532
	70	74.10	75.1	-1,00	-1,332
	80	77.30	79.2	-1,90	-2,399
75	0	29.00	29.0	0,00	0,000
	10	47.20	48.2	-1,00	-2,075
	20	58.20	58.5	-0,30	-0,513
	30	70.10	69.3	0,80	1,154
	40	78.60	78.0	0,60	0,769
	50	86.10	86.3	-0,20	-0,232
	60	92.80	93.7	-0,90	-0,961
100	0	30.10	29.9	1,01	3,472
	10	51.90	52.6	-0,70	-1,331
	20	64.20	64.7	-0,50	-0,773
	30	72.30	72.7	-0,40	-0,550
	40	80.80	81.6	-0,80	-0,980
	50	88.80	89.2	-0,40	-0,448
	60	96.50	97.7	-1,20	-1,228
	70	102.00	102.0	0,00	0,000

During experiments the environmental laboratory conditions were constant, with a relative humidity of 62% and 27°C temperature in the air and is assumed to be equal to atmospheric conditions (measurements were made in June). No dust or liquid droplets which can have influence of infrared transmissivity have noticed [7].

The pump temperature was measured, in the same time and relativelly in the same place on the pump's surface, with FLIR thermal imaging camera (see Table I) and FLUKE infrared thermometer (see Table II) to compare and validate the use of FLIR thermal imaging camera method as a method of preventive maintenance in hydraulic drive systems. The distance from the gear pump surface was the same at 0.5m for all measurements.

TABLE II. PUMP TEMPERATURE MEASUREMENTS WITH THROTTLE

Pressure (bar)	Time (min)	Temperature (°C)		T_{ab_ST} (°C)	Error $\varepsilon_{T_{ab\_ST}}$ (%)
		FLUKE T_{IT}	FLIR T_{IC}		
50	0.00	27.80	27.7	0,10	0,3610
	10.00	53.60	53.4	0,20	0,3745
	20.00	61.70	60.2	1,50	2,4917
	30.00	65.30	66.9	-1,60	-2,3916
	40.00	70.60	71.4	-0,80	-1,1204
	50.00	74.70	76.5	-1,80	-2,3529
	60.00	79.20	80.1	-0,90	-1,1236
	70.00	82.60	83.6	-1,00	-1,1962
	80.00	86.90	87.9	-1,00	-1,1377
75	0.00	25.00	25.0	0,00	0,0000
	10.00	51.00	57.2	-6,20	**-10,8392**
	20.00	72.00	78.4	**-6,40**	-8,1633
	30.00	77.00	84.1	-7,10	-8,4423
	40.00	83.00	86.3	-3,30	-3,8239
	50.00	90.00	88.3	1,70	1,9253
100	0.00	29.20	29.6	0,14	0,4818
	10.00	56.40	57.7	-1,30	-2,2530
	20.00	65.70	70.6	-4,90	-6,9405
	30.00	75.20	79.4	-4,20	-5,2897
	40.00	84.30	85.6	-1,30	-1,5187
	50.00	92.20	92.7	-0,50	-0,5394

In all experiments wiht suction throttle ST, the flow aria of the throttle ST was the same in all cases of prresure steps.

Both FLUKE IT thermometer and FLIR IC have their own calibration and emissivity coefficient. So, FLUKE IT emissivity coefficient was $\varepsilon_{IT} = 0.95$ and FLIR IC emissivity $\varepsilon_{IC} = 0.93$.

Using the measured temperatures from tabels I and II was plotted the temperature evolution in the case of a malfunction with ST partial opened on the suction pipe and the proper operation mode, without ST. The temperatures measured with infrared thermometer IT were plotted with line and marker, and temperatures which were measured with infrared cameras IC were plotted only with a type of marker available on each pressure step of 50bar, 75bar and 100bar. In figures 2 to 4 are graphically represented the results.

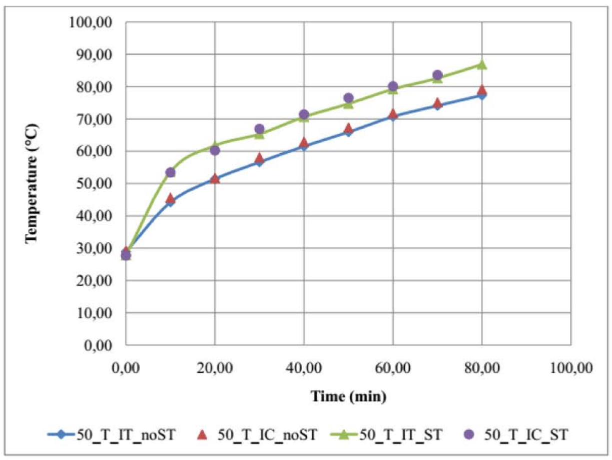


Figure 2. Temperature measurements with/without ST and pressure 50bar

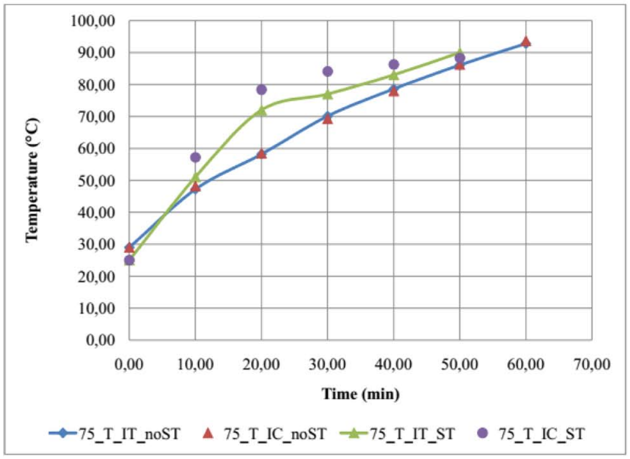


Figure 3. Temperature measurements with/without ST and pressure 75bar

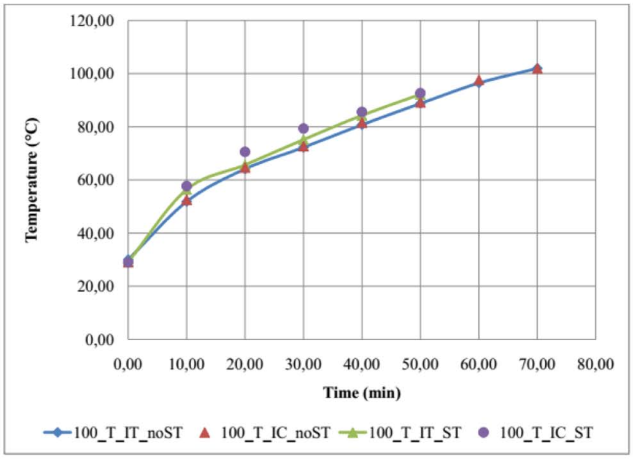


Figure 4. Temperature measurements with/without ST and pressure 75bar

To estimate if the infrared thermal imaging camera can be used as a predictive maintenance method, the absolute errors (T_{ab_ST} and T_{ab_noST}) in the case of with ST and without ST were calculated in Table I and II, as difference between the temperature measured with infrared thermometer (T_{IT}) and temperature measured with infrared camera (T_{IC}) [5]:

$$T_{ab} = T_{IT} - T_{IC}. \qquad (1)$$

The relative error of the infrared imaging camera used as predictive maintenace method is the ratio of absolute error T_{ab} to temperature T_{IT} measured with infrared thermometer [5]:

$$\varepsilon_{T_{ab}} = \frac{T_{ab}}{T_{IC}}. \qquad (2)$$

The last column of Table I and II have the relative errors for each pressure step and each operating mode, with ST and without ST.

Based on tables I and II, temperatures avarage ($\bar{T}$), standard deviation (σ), and precission of the method (p_{method}) used in temperature measurement have been estimated using the relations (3) to (5):

$$\bar{T} = \frac{1}{N}\sum_{i=1}^{N} T_i, \qquad (3)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(T_i - \bar{T})^2}{N}}, \qquad (4)$$

$$p_{method} = \frac{\sigma}{\sqrt{N}}, \qquad (5)$$

where N are the number of measurements in each case of experimental simulations and T_i are the measured temperatures. The results are listed in Table III where the abbreviations used have the meanings of:

- IT_noST, infrared thermometer method and without ST the operating mode of the gear pump;
- IT_ST, infrared thermometer method and with ST the operating mode of the gear pump;
- IC_noST, infrared imaging camera method and without ST the operating mode of the gear pump;
- IC_ST, infrared imaging camera method and with ST the operating mode of the gear pump.

TABLE III. STATISTICAL DATA TEMPERATURE MEASUREMENTS

		Pressure (bar)		
		50	***75***	***100***
Average (°C)	IT_noST	58,96000	66,00000	73,32500
	IC_noST	**60,10000**	66,14286	73,69880
	IT_ST	66,93000	66,33330	67,16670
	IC_ST	67,52000	69,88333	69,17670
Standard deviation (°C)	IT_noST	15,58124	22,66091	24,10230
	IC_noST	15,91383	22,64294	24,48560
	IT_ST	18,01802	24,19642	22,55790
	IC_ST	18, 59716	24,73341	23,11140
Precission (°C)	IT_noST	5,19375	8,56020	8,52140
	IC_noST	5,30461	8,55823	8,65720
	IT_ST	6,01802	9,87815	9,20920
	IC_ST	6,19905	10,09737	9,43520

Statistical data in Table III characterized the error and uncertainty of the temperature method used in the experiments.

IV. DISCUSSIONS

A thermogram helps us to visualize like in an X-ray the object structural integrity and fluid continuity inside the object, pump in our case study as it could be seen in Figure 1-c. These aspects come to emphasize the advantages of infrared thermography.

The results obtained reveal a good match of the measurements made by the two methods (thermal imaging cameras and infrared thermometer). The absolute error is maximum 6.4°C (corresponding to the relative error of 8.1633%) respectively a maximum relative error of 10.8392 % which correspond to an absolute error of 6.2°C.

Also, the results obtained show a good match with the physical phenomena that occur during the operation of the drive system to simulate the operation of the gear pump in case of failure. So the figures in which the results were plotted (Figures 2 to 4) are seen that the temperatures are higher when the pump is operating with suction throttle ST on the supply pipe then in the case of without ST for all pressure steps. Section narrowing when flowing a fluid causes a pressure loss in the hydraulic circuit and the heating of the fluid. Also, it is observed that for the same time of the experiments, in the case of pump operation with suction throttle, the heating of the oil is much faster and the cavitation phenomenon occurs. For this reason, the measurements in the case of pump operation with suction throttle are stopped after 50 minutes both 75bar and 100bar pressure.

From the point of view of the working method, the statistical results in Table III can be improved. Can be observed that low precision is reflected in a high degree of uncertainty whose values are increasing at higher pressure steps. But, it is also noted that the degree of uncertainty is comparable between the two methods used, which is justified by the fact that the methods have the same physical basis, the measurement of the infrared radiation level.

The uncertainty of the method can be reduced by minimizing errors and the total emissivity, ε, of an object depends on "wavelength λ, temperature T, material, state of the surface, direction of observation, polarization and also-in ultrafast thermal process-on time" [5]. For example, the error in temperature depends on the uncertainty in total emissivity [3]:

$$\Delta T \approx 0.25 \cdot T \cdot \frac{\Delta\varepsilon}{\varepsilon}, \quad (6)$$

where Δε is tolerance on the total emissivity. In Figure 5 the error in temperature variation is plotted for different uncertainties in total emissivity which are between the object and thermal imaging camera, or infrared thermometer. The temperature considered is one of the values in Table III, the average of 60.1°C. If the pump emissivity is considered ε=0.95 (oxidized metal surface [2]) for an emissivity error of 0.25 the temperature error is ΔT=3.953947°C.

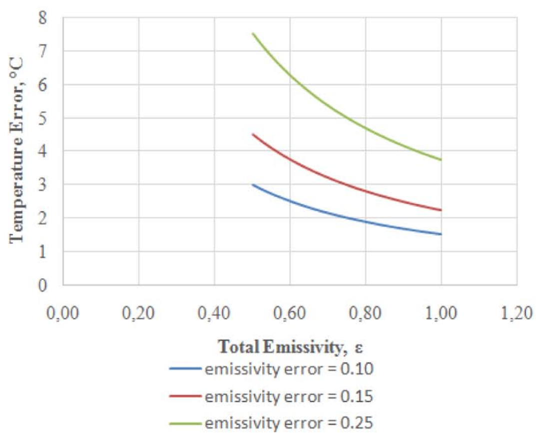


Figure 5. Temperature error depends on emissivity error

In our future work is some important changes must be done to improve the experiments protocol:

- to determine the true emissivity of pump surface;

- to calibrate the thermal infrared camera considering as the reference in temperature measurements a contact thermometer;

- to determine the influence of the distance between the infrared cameras and the pump;

- to monitor the environmetal condition in the laboratory troughout the measurements;

- to record the measurement results at five-minute intervals instead of ten as they were.

V. CONCLUSIONS

Experimental simulations were carried out on the posibility of using the infrared termography method as a tool in predictive maintenance program applied in hydraulic drives.

Infrared thermography can be used as a qualitative method, and by increasing accuracy of measurements it can also be used as a quantitative method in the predictive evaluation of the behavior of hydraulic equipment.

The measurement results have relative errors that fall within the range of ±12%, but the results can be improved changing the way in which the temperature reference was measured. Instead an infrared thermometer which have its emissivity with a degree of uncertainty, a contact thermometer will be used.

ACKNOWLEDGEMENTS

This paper has been developed in INOE 2000-IHP, with the financial support of the Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI), under PN III, Programme 2- Increasing the competitiveness of the Romanian economy through research, development and innovation, Subprogramme 2.1- Competitiveness through Research, Development and Innovation - Innovation Cheques, project title: "Method for assessing the wear and the functionality degree at pumps and hydraulic cylinders through infrared termography", Financial Agreement no. 8 CI/2017.

REFERENCES

[1] Dhillon, B.S., Engineering Maintenance. A Modern Approach, CRC Press, 2002, pp. 13-15.

[2] Mobley R. Keith (ed.), Maintenance Engineering Handbook, 7th Edition, McGraw-Hill, 2008; Section 7. Instruments and Reliability Tools (by Mobley R. Keith), pp. 7.105-125.

[3] Childs P. R N., Practical Temperature Measurement, Butterworth Heinemann, 2001, pp. 238-287.

[4] Mihai, Al. Termografia în infraroşu. Fundamente, Ed. Tehnică, Bucureşti 2005.

[5] Minkina, W., Dudzik, S., (2009), "Infrared Thermography. Errors and Uncertainties". Ed. Wiley & Sons.

[6] Madding R.P., (1999), "Emissivity measurement and temperature correction accuracy considerations", Proceedings of the SPIE, Vol. 3700, pp. 393–401, 1999.5.

[7] Chisacof Al., Dimitru S., Dragostin C., Temperature Field From Free Two Phase Jet Using Infrared Equipment, Termotehnica J., No 2, 2011, pp. 61-64.

[8] http://web.itu.edu.tr/yildiri1/fa11ee432/docs/fluke66.pdf.

[9] http://www.testequipmentdepot.com/extech/pdf/infracam.pdf.