Liquid property control system for LVAD ISO 5198 testing and mock circulatory loop simulations.

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Abstract— **Determination of performance for fluid power systems through a range of operating conditions is a crucial aspect of safety assurance. Experimental confirmation supports the computational design and verification steps taken to ensure the mechanism will perform adequately. Pumps, valves and other devices destined for hydraulic can have their performance be subject to differences in the fluid properties of the liquid. This necessitates that a range of fluid properties be examined to ensure that the operating envelope is properly characterized. Past approaches to these experiments have involved modifying the system fluid manually and only investigating a sparse set of conditions. Proposed is a liquid property unit that is able to make changes to a system fluid of a bench testing apparatus used to evaluate hydraulic devices. The chosen fluid system for the initial release of this design is a water:glycerin composition. The intent is to have a fluid chemistry that has a broad range of densities and viscosities. This unit is controlled via a user interface and is able to execute set point changes to the system fluid and maintain the total system volume desired. The design of the system, validation of its operation and use of the fluid in exemplary trials will be covered.**

Keywords—Fluid properties, viscosity, density, peristaltic, verification, graphical user interface, Arduino, Refutas Equation

I. Introduction

This The Liquid Property Control Unit (LPCU) is a system designed to change the characteristics of fluid inside of a mock circulatory loop (MCL). MCLs are used to simulate the conditions in the heart in order to assess the viability of cardiovascular assistive devices. It's important to test cardiovascular assistive devices in a wide range of conditions in order to verify that they are safe. This principle extends to the blood substitute that is used to simulate the viscosity and density of blood. However, changing the liquid in a MCL can be a time consuming process, susceptible to human error, that requires the attention of the operator of the mock circulatory loop. The LPCU is designed to automate this process to not only save time, but allow the property change to be scheduled through a graphical user interface (GUI) so that the user doesn't have to be present to run simulations.

II. System Design

The LPCU is controlled with an Arduino Mega 2560 microcontroller programmed with the Arduino IDE and interacted with via a GUI created in Mathworks MATLAB at a baud rate of 9600 bits-per-second. The GUI that controls the LPCU has four fields that the user must fill out: existing kinematic viscosity, desired kinematic viscosity, desired density, and the volume in the MCL. The GUI sends this information to the Arduino via serial communication. The Arduino controls the two Bartendro peristaltic pumps, the four solenoid valves that comprise the LPCU, and does the necessary computations for the operation of the unit. Three base fluids kept in large pales are each drawn through 0.25" tubing that connect to individual solenoid valves. On the other side of the valves, the tubes converge into one, which connects to the Bartendro pump that is responsible for adding fluid into the MCL. The solenoid valves are activated via a 12V electrical relay that is triggered by the Arduino's digital pins and the Bartendro pumps are powered by a 12V power source plugged into a DFRobot 2A motor shield. The other Bartendro pump draws fluid from the MCL and takes it straight to a waste pale.

III. Governing Equations

The Arduino is programmed to accept four values from the user: existing kinematic viscosity(EV) in centistokes (cSt), desired kinematic viscosity (DV) in cSt, desired density (DD), and the current volume in the loop (VL). The Refutas Equation is used to calculate the viscosity of a blend of fluids. The Viscosity Blending Number (VBN) of each component must be calculated at the same temperature using the kinematic viscosity (v) in cSt. Then, the VBN of the mixture is obtained by adding the VBN multiplied by the mass fraction of each component together. Once the VBN of the solution has been determined, we used the reverse of the first equation to find the viscosity of the blend. The three parts of the Refutas equation are shown below.

$$VBN = 14.534 \times \ln\left(\ln(v + 0.8)\right) + 10.975 \tag{1}$$

$$VBN_{blend} = [x_A \times VBN_A] + [x_B \times VBN_B] + \cdots + [x_N + VBN_N] \tag{2}$$

$$v = \exp\left(\exp\left(\frac{VBN_{Blend} - 10.975}{14.534}\right)\right) - 0.8 \tag{3}$$

Using the Refutas Equation, the Arduino can determine the viscosity of the blend that needs to be added to the mixture by holding the mass fraction of the mixture being removed (0.53), as well as the mass fraction of the saturated sodium solution (0.1) constant. The modified equation used to determine the VBN of the solution that needs to be added is as follows:

$$VBN_{Input} = \frac{\{[\ln(\ln(DV+0.8))\times 14.534] + 10.075\} - \{[\ln(\ln(EV+0.8))\times 14.534] + 10.075\}\times 0.53}{0.47} \tag{4}$$

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Once the VBN of the inputted solution (VBN_{input}) has been determined, the Arduino uses (2) to determine the mass fraction of water:glycerin and water of the solution that will be added to the loop. Using the known densities and the calculated mass fractions of each base fluid a well as the desired density and current volume inputs from the user, the Arduino calculates the volume of each base fluid that needs to be added to the loop. The Arduino always removes a mass fraction of 0.53 from the loop before adding fluid to it, so the volume of the fluid to be removed is calculated as well.

IV. Operation of the Unit

In order to begin a fluid property change, the user must first connect the GUI to the Arduino by inputting the COM port number into the GUI and pressing the "Connect" button. The GUI will notify the operator once it is connected, allowing them to begin filling out the fields labeled "Existing Viscosity", "Desired Viscosity", "Desired Density", and "Total Volume". Once these fields are completed, the user simply presses "RUN", beginning the property change process. Throughout the process, the GUI will keep the user informed on whether it's removing or adding fluid to the loop, and will give an estimated run time for the entirety of the process.

V. Methods Testing

In order to validate the results of the LPCU, we first needed to ensure that the methods of measurement being used to validate those results were correct. To accomplish this, we tested the density and viscosity of three known mixtures using the viscometer, volumetric pipette, and balance that would be used to test the mixtures made by the LPCU. The results shown in Table 1 next to the theoretical values (T.) validated our means of measurement. However, it was discovered that the viscometer we were using only has an effective range of 1.6 to 6.4 cSt. Human blood ranges from 3 to 4 cSt, so this will not be an issue when testing mixtures made by the LPCU. This does pose a challenge in measuring the viscosity of the glycerin:water base liquid, but using orthogonal measurements such as density and refractive index (R.I.) will be sufficient in confirming that the base liquid has the necessary properties for the entirety of the process.

VI. Exemplary Trials and Conclusions

Once we'd established that out measurement tools were accurate, we ran our first exemplary trial, the results of which are found in Table 2. One of the tenants of the LPCU is to maintain a constant volume in the mock loop. Throughout all three trials, the LPCU maintained a precise volume of 1.00 L, meaning that the Bartendro pumps were accurately dispensing the volume that the Arduino program calculated. Although the density and viscosity were not accurate, the system demonstrated its ability to remove and add volume to the loop while changing the characteristics to be closer to the target characteristics than it was initially. The conclusions that we've drawn from this first trial is that the system works correctly, but the base liquids are not accurate or consistent. This issue will be resolved in future work

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Table I.

Results from testing viscosity, density, and volume measurement methods

Glycerin-Water Mixture	T. Density	Measured Density	% Error	T. Viscosity	Measured Viscosity	% Error
40/60 glycerin-water	1.11 g/mL	1.12 g/mL	0.90%	3.12 cSt	3.14 cSt	0.64%
50/50 glycerin-water	1.14 g/mL	1.16 g/mL	1.75%	4.98 cSt	4.94 cSt	0.80%
60/40 glycerin/water	1.26 g/mL	1.25 g/mL	0.79%	8.72 cSt	7.90 cSt	9.40%

Table II.

Results from first exemplary trial

	Initial Properties			Target Properties			Final Properties		
	Density	Viscosity	Volume	Density	Viscosity	Volume	Density	Viscosity	Volume
Container 1	1.102 g/mL	2.81 cSt	1.00 L	1.125 g/mL	3.50 cSt	1.00 L	1.114 g/mL	3.52 cSt	1.00 L
Container 2	1.104 g/mL	3.00 cSt	1.00 L	1.125 g/mL	4.00 cSt	1.00 L	1.252 g/mL	3.86 cSt	1.00 L
Container 3	1.103 g/mL	3.17 cSt	1.00 L	1.125 g/mL	4.00 cSt	1.00 L	1.119 g/mL	3.83 cSt	1.00 L