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PID POWER CONTROLLER TO A SETPOINT OF FLUID LEVEL HEIGHT IN A RESERVOIR FOR UNATTENDED HUMAN MONITORING

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ABSTRACT: *This paper provides a novel approach of a power control system of a fluid tank pump to reach a specific setpoint of fluid level height. The system enables users to fill a tank to any desired height within a chosen time interval. The system is equipped with a timer that allows the user to fill the tank to the desired level within the desired time. The system is based on utilizing a Proportional Integral and Derivative (PID) controller to adjust the pump's power to satisfy the user-defined setups (time and fluid level height). This approach has the potential to be applied for domestic purposes for unattended human monitoring. This approach has been demonstrated using LabVIEW coding to apply the fluid and hydrodynamic design and control principles. The results have illustrated the code's capability to achieve the desired tank fluid level height for a variable range of fluid level height setpoints and time intervals*

KEYWORDS: PID controller, Power Controller, Unattended Human Monitoring,

INTRODUCTION

The currently available conventional fluid pumping systems still require direct human monitoring, consuming both the users' time and exposing the system to human errors [1]. Integrating automatic control systems into the existing pumping systems eliminates human errors and saves the users' time. Although the literature [2-9] has provided a wide range of optimization approaches, the criterion of computational simplicity, system adaptation to the user specification, and cost are compromised rather than ensured. The references [2-4] have managed to provide an automatic control approach to be integrated into the conventional setups of domestic fluid pumping systems. Those approaches have demonstrated their capabilities to adjust the system's performance based a wide interval of user-defined setups; however, the proposed methods were computationally complex, thus affecting the systems performance speed. The references [5-7] have proposed the Multi-Model Predictive control (MPC) method to overcome this obstacle. However, the economic sustainability of applying the MPC control method remains a challenge [8-9]. Therefore, this paper aims to provide a novel

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approach to controlling a fluid pumping system based on the desired user defined time interval and to adjustable fluid level. The proposed system has the ability to adapt with wide intervals of user setups (time and fluid level heights). In addition, the computational complexity has been reduced by implementing the final governing Equation of the proposed hydrodynamic system. Finally, due to the simple and commercially available setup of the proposed fluid pumping system, the cost of applying the proposed method is anticipated to be within the acceptable economic margins.

MATERIALS AND METHODS

Design overview

A code has been developed using the LabBVIEW software [10]. The LabVIEW software provides a visual programming language and is equipped with a User Interface (UI) to simulate a wide range of industrial applications. Therefore, this paper utilized the software to simulate the performance of a power controllable pump integrated with a fluid tank and a Proportional, Integral, and derivative (PID) controller, Figure 1. As shown in Figure 1, the user interface has been designed as a 'user-friendly' control panel with performance control and monitor features. The control features give the user the privilege of controlling the system manually or automatically by specifying the PID gains to achieve a specific desired fluid level height. The user can shift the system from the manual mode into the automatic mode using the 'controller ON/OFF' Boolean switch. The system can also be controlled by the primary 'system' Boolean switch, which turns the system on or off, the timer knob to specify the desired time to fill the tank to the desired fluid level, the vertical fill slider of the desired fluid level height and the pump adjustable power. Once the system is switched to the automatic mode, it adjusts the pump's power based on the desired time of filling the tank to the user specified fluid level height. The monitoring features are the corresponding numerical and visual representation 'graphics' of the actual fluid level height and the controlled pump power.

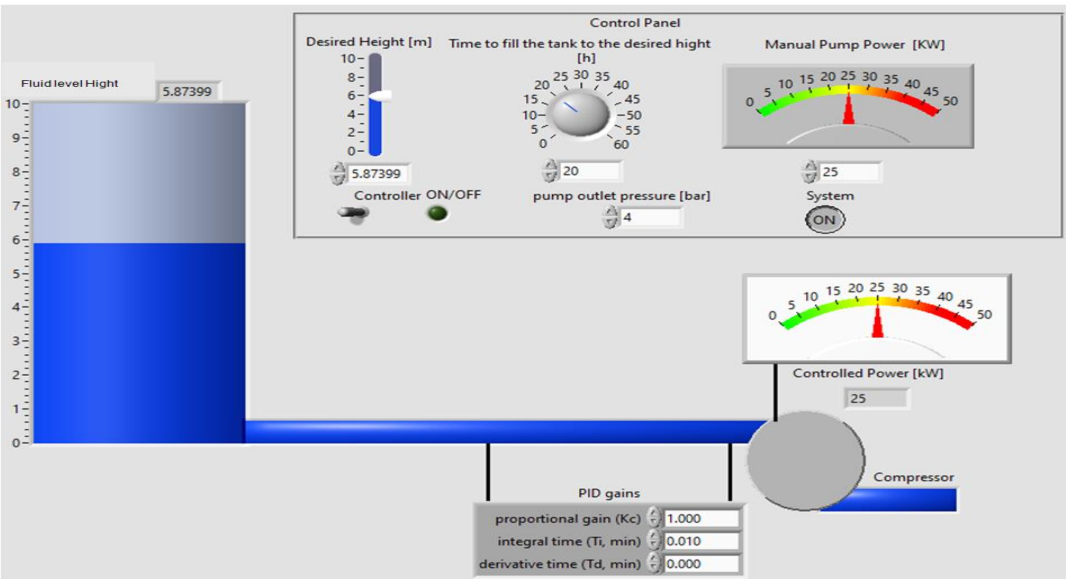

Figure 1. User Interface of the code.

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Coding and numerical derivation

The User interface has a parallel block diagram –Figure 2- which corresponds to the user inputs and allows the conduction of the numerical formulas, and performs the logical programming sequence. However, numerical derivation of the governing hydrodynamic and fluid dynamic Equation shall be initiated in advance to reduce the complexity of the block diagram. Therefore, this section discusses the derivation of the final governing numerical formula of the designed setup, specifies the adopted set of assumptions, and highlights the logical programming sequence of the code. For the provided design specifications and the adopted set of assumptions in Table 1, the numerical derivation of the governing Equation of the code has been initiated with the Equation (1) [11], which correlates the pump power (Wp) to the fluid mass flow rate ($\dot{m}f$), isobaric heat capacity (Cp) and the final and initial temperatures of the working fluid ($T02$ and $T02$, respectively).

$$W_p = \dot{m}_f C_p (T_{02} - T_{01}) \quad (1)$$

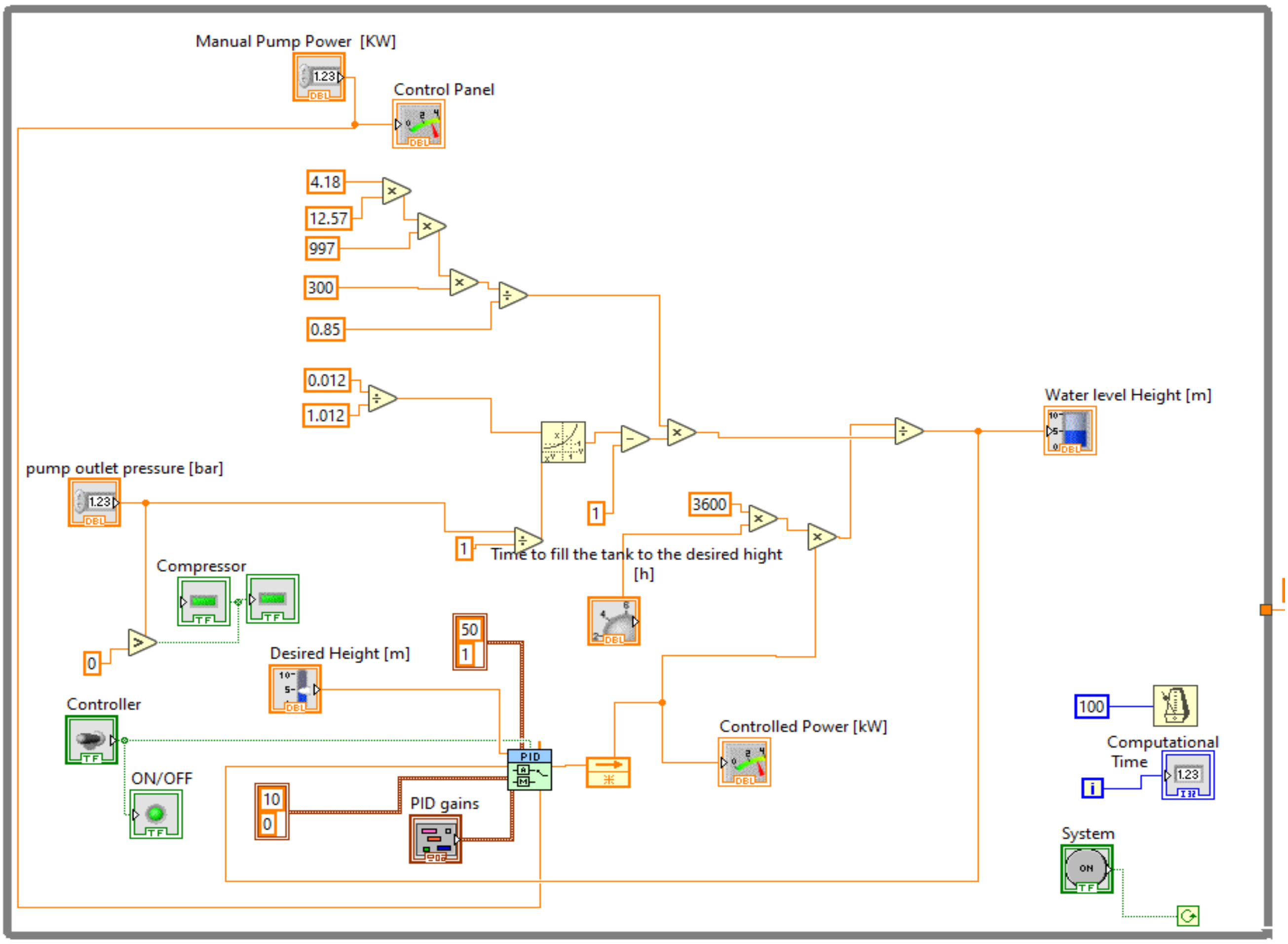

Figure 2. Block diagram of the pump-tank-controller system.

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By solving the Equation (1) for $\dot{m}_f$, the Equation (1) is rearranged into Equation (2). Since the mass flow rate ($\dot{m}_f$) is related to the fluid volumetric flow rate ($\dot{V}_f$) and density (ρ_f) by the Equation (3) [12], the Equation (2) can be expanded into Equation (4).

$$\dot{m}_f = \frac{W_c}{C_p(T_{02} - T_{01})} \tag{2}$$

$$\dot{m}_f = \rho_f \dot{V}_f \tag{3}$$

$$\rho_f \dot{V}_f = \frac{W_c}{C_p(T_{02} - T_{01})} \tag{4}$$

The volumetric flow rate in the tank ($\dot{\mathbf{V}}_\mathbf{f}$) can be written in terms of the rate of change of fluid level high ($\dot{\mathbf{h}}$) and cross-sectional area of the tank (A) as expressed in Equation (5) [12]. As shown in Table 1, the tank has a cylindrical shape, thus, the Area (A) can be written as shown in Equation (6). Furthermore, the rate of change of the fluid level high ($\dot{\mathbf{h}}$) is governed by equation (7) [12] [13] [14] [15]. By substituting Equations (6) [16] [17] [18] and (7) into Equation (4), the Equation (4) [19] [20] [21] can be expanded into equation (7) [22] [23].

$$\dot{V}_f = \dot{h}A \tag{5}$$

$$A = \pi r^2 \tag{6}$$

$$\dot{h} = \frac{\Delta h}{\Delta t} \tag{7}$$

$$\rho_f \frac{\Delta h}{\Delta t} \pi r^2 = \frac{W_c}{C_p(T_{02} - T_{01})} \tag{8}$$

Solving the Equation (8) for the change of fluid level high ($\Delta\mathbf{h}$) yields Equation (9). The final temperature of the fluid can be expressed in terms of the pumps isentropic efficiency ($\boldsymbol{\eta}_\mathbf{c}$), the fluids specific heat capacity ($\boldsymbol{\gamma}_\mathbf{f}$), initial temperature ($\mathbf{T}_{\mathbf{01}}$), initial and final pressure ($\mathbf{P}_{\mathbf{01}}$and $\mathbf{P}_{\mathbf{02}}$, respectively) as shown in Equation (10)[11].

Table 1. Design specifications

Property	Value/interval
Pump power capacity [kW]	[0-50]
Timer interval [h]	[0-60]
Height setpoint [m]	[0-10]
Pump outlet pressure [bar]	4
Pump isentropic efficacy [%]	85
Tank Shape	Cylindrical
Tank height [m]	10
Tank cross-sectional area $(A = \pi r^2)$ $[m^2]$	12.7
Tank maximum volume capacity $[m^3]$	127.7
Ambient pressure and temperature [bar, K]	[1,300]
Working fluid type	water
Working fluid density $(\rho_f)[kg/m^3]$	997
Working fluid isobaric heat capacity (C_p) [kJ/kg.K]	4.18
Working specific heat capacity (γ_f)	1.012

The pump's outlet pressure and isentropic efficiency are in accordance with the reference [12]. The working fluid properties (ρ_f,C_p, and γ_f) at the specified ambient condition [1bar and 300K] are in accordance with the reference [13].

Therefore, by substituting Equation (10) into (9), the governing Equation of the change of the fluid level height (**Δh**) can be expressed as Equation (11) which is a function of the user-defined and controllable inputs (the desired time to fill the tank (**Δt**) and the pump work (**W_c**)).

$$\Delta h = \frac{W_c \Delta t}{C_p \pi r^2 \rho_f (T_{02} - T_{01})} \tag{9}$$

$$T_{02} = \frac{T_{01}}{\eta_c}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{(\gamma_f - 1)}{\gamma_f}} - 1 \right] + T_{01} \tag{10}$$

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$$\Delta h = \frac{W_c \Delta t}{C_p \pi r^2 \rho_f \frac{T_{01}}{\eta_c}\left[\left(\frac{P_{02}}{P_{01}}\right)^{\frac{(\gamma_f - 1)}{\gamma_f}} - 1\right]} \quad (11)$$

Complying with design specification in Table1, governing Equation of $\boldsymbol{\Delta h}$ can be reduced into a function with only two variables ($\boldsymbol{\Delta t}$ and $\boldsymbol{W_c}$), and the remaining parameters are constant, which correspond to the design specification, Equation (12). Refereeing to the block diagram, the Governing Equation (12) has been implemented in the sequence shown in Figure1.

$$\Delta h = \frac{W_c \Delta t}{(4.18)(12.7)(997)\frac{300}{85\%}\left[\left(\frac{4}{1}\right)^{\frac{0.012}{1.012}} - 1\right]} \quad (12)$$

Finally, the LabVIEW defined PID controller computational block-Figure3- has been integrated into the block diagram as shown in Figure 1. The user-defined pump power data is transferred to the PID block as the manual input within the interval of [1-50] kW, while the desired height($\mathbf{h_d}$) is used as the setpoint within the interval of [0-10]m. Therefore the error $\mathbf{e(t)}$of the PID controller is shown expressed as in Equation (13) and the PID block computes the adjusted power of the pump as the processed variable ($\mathbf{u(t)} = \mathbf{W_p(t)}$) as shown Equation (14). The proportional gain ($\mathbf{K_c}$), the integral time ($\mathbf{t_i}$), and the derivative time ($\mathbf{t_d}$) have been identified by a set of numerical attempts as $\mathbf{0.01}$, $\mathbf{0.6}$ [ms], and $\mathbf{1}$[s], respectively.

$$e(t) = h_d - \Delta h(t) \quad (13)$$

$$W_p(t) = K_c\left[e(t) + \frac{1}{t_i}\int_0^t e(t')dt' + t_d\frac{de(t)}{dt}\right] \quad (14)$$

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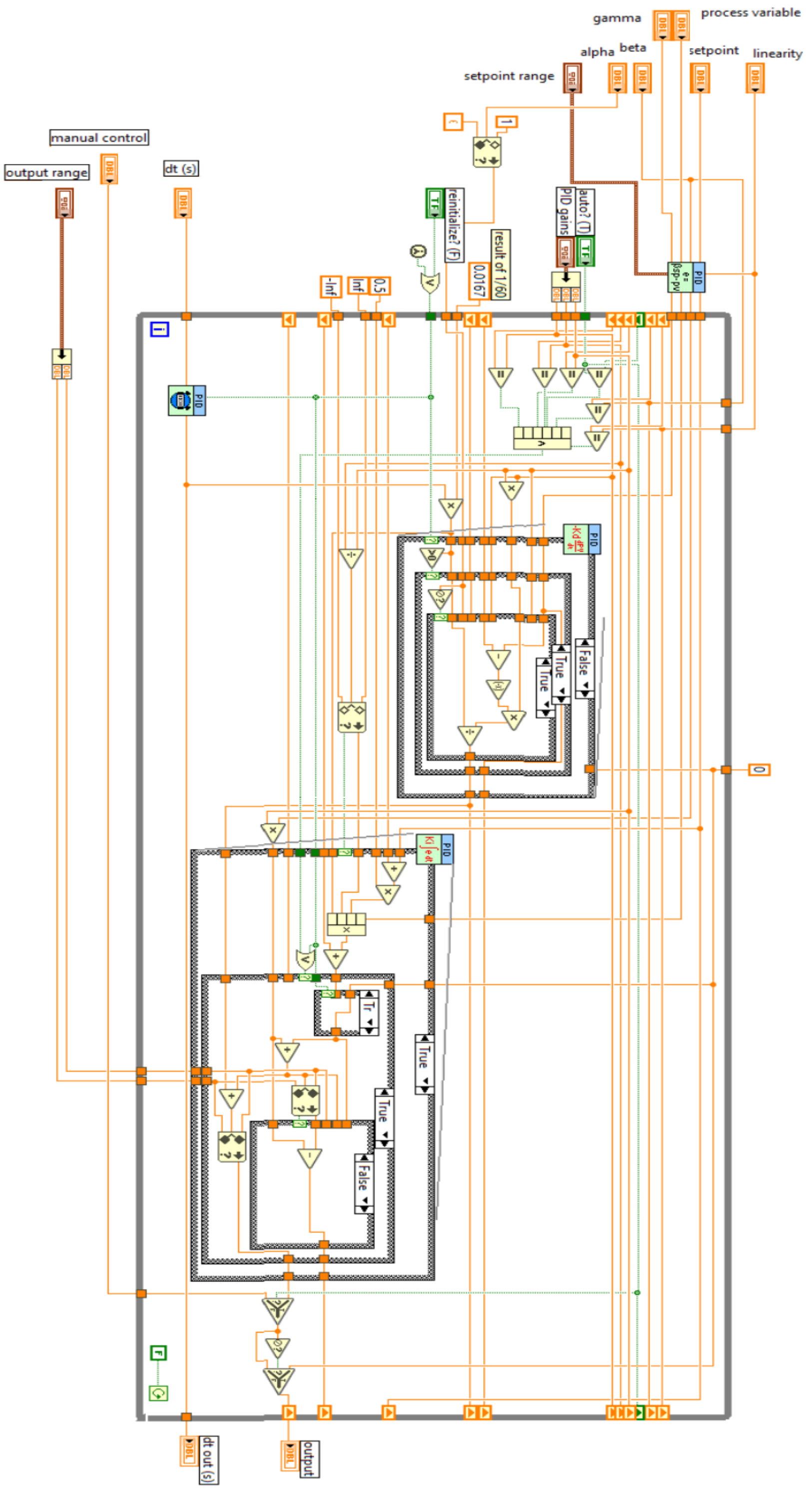

Figure 2. Block diagram of the adopted LabVIEW Proportional, Integral and Derivative PID(controller)

RESULTS

Systems performance for variable intervals of fluid level height and time.

Corresponding to the design specifications in Table 2, this section demonstrates the systems capability by a case of study in which the system is required to adjust the pumps power to fill the tank to a fluid level height of 5 m within 20h. As shown in Figure 4, the code manages to reach the required fluid level height by adjusting the pump's power to 21.3 kW, thus filling the tank within the desired time.

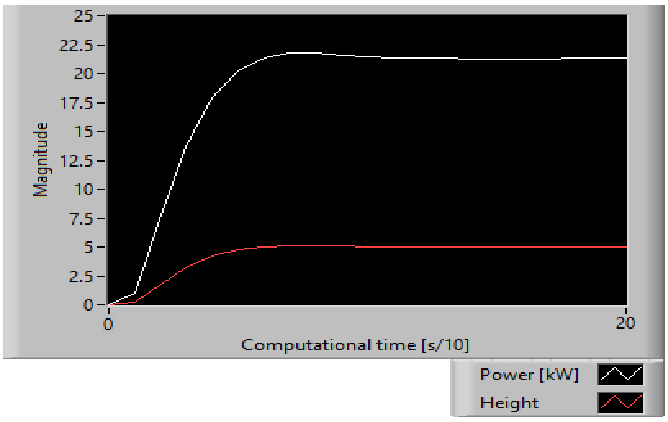

Figure 4. System performance to fill the tank to 5 m within 20 h. (Note: the computational time is the calculation time required by the code).

The system performance has been further examined for another case of study where the desired time to fill the tank has been changed to 30h, and the desired fluid level height has been changed to 9 m. Similarly, as shown in Figure 5, the system has managed to reach the desired fluid level height of 9 m by adjusting the pump's power to 25.53 kW to fill the tank within the desired time.

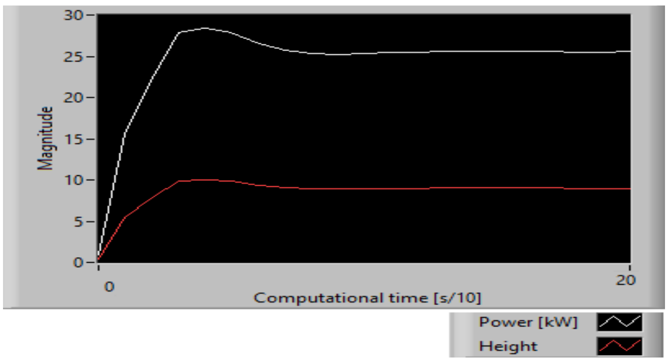

Figure 5. System performance to fill the tank to 9 m within 30 h. (Note: the computational time is the calculation time required by the code).

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Systems performance for variable intervals of pump outlet pressures and isentropic efficiency.

As the system has demonstrated its capability of adjusting the pump's power for two variable intervals of time and fluid level height, the systems capability has been further examined for a variety of pumps types and capabilities. The has been performed by studying the systems performance for variable values of isentropic efficiency and compressor outlet pressure.

Figure 5 shows the system's performance corresponding to the setup specified in Table 1. For this case of study, the desired fluid level height is 7m and the desired time to fill the tank has been chosen to be 25h. In addition, to demonstrate the systems capability of adapting with pumps with different outlet pressure (i.e., other than 4 bar, Table1), the outlet pressure has been chosen to be 6 bar. As shown in Figure 6, the system has managed adapt with the 6 bar outlet pressure to reach the desired fluid level height of 7 m by adjusting the pump's power to 30.8 kW to fill the tank within the desired time (25h).

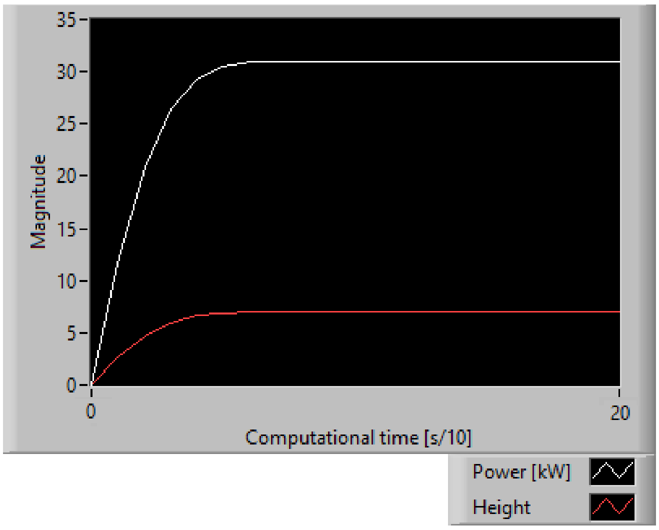

Figure 6. System performance at pump outlet pressure of 6 bar to fill the tank to 7 m within 25 h. (Note: the computational time is the calculation time required by the code).

Similarly, to demonstrate the systems capability of adapting with pumps with different isentropic efficiencies (i.e., other than 85%ar, Table1), the isentropic efficiency has been reduced to 80%. For this case of study –Figure 7- the desired fluid level height, desired time to fill the tank and pump's outlet pressure have been maintained as the previous case (Figure 6)(i.e. 7m, 25h and 6 bar).

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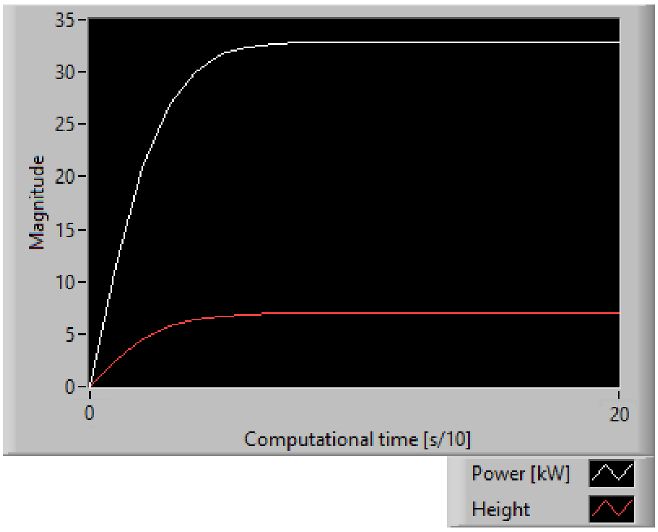

Figure 7. System performance at pump outlet pressure of 6 bar with the isentropic efficiency of 85%, to fill the tank to 7 m within 25 h. (Note: the computational time is the calculation time required by the code)

As shown in Figure 6, compared to the previous case (Figure 5, isentropic efficiency is 85%), the pump's power has been increased from 30kw to 32.8 kW to reach the desired fluid level el height within the desired time (7 m within 25 h), thus, indicating the systems capability of identifying the pump's power with lower isentropic efficiency (<85%).

DISCUSSION AND CONCLUSION

This paper has provide a novel approach to controlling a fluid pumping system based on the desired user defined time interval and to adjustable fluid level. The proposed system has the ability to adapt with wide intervals of user setups (time and fluid level heights). In addition, the computational complexity has been reduced by implementing the final governing Equation of the proposed hydrodynamic system (i.e. the computational time <10s). The system can be controlled manually and automatically. Once the system is switched to the automatic mode, it adjusts the pumps power based on the desired time of filling the tank to the user-specified fluid level height. The system has demonstrated its capability to identify the required pump power to 21.3 kW and 25.53 kW to reach the desired fluid level heights of 5m and 9m within the desired time interval 20 h and 30 h, respectively.

Moreover, the systems capability of adapting with a verity of pump capabilities have been demonstrated for a range of pump's outlet pressure and isentropic efficiencies. The system has identified the pump's power for the outlet pressure of 6 bar and 4 bar and for pump's isentropic efficiencies of 80% and 85%. Therefore, showing the potential to be applied for a wide range of industrial applications and existing setups without the necessity of performing major amendments

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Finally, due to the simple and commercially available setup of the proposed fluid pumping system, the cost of applying the proposed method is anticipated to be within the acceptable economic margins. In real case scenarios, the time intervals will be specified using a timer which will also be synchronized to the primary switch, thus switching the pumps power off when the desired conditions are achieved. Therefore, the designed setup allows unattended human monitoring of fluid level and has the potential to be applied for domestic purposes.

Nomenclature

W_c	Compressor Power [kW]
$\dot{m}_f$	Fluid mass flow rate [kg/s]
C_p	Heat capacity at constant pressure [kJ/kg.K]
γ_f	Specific heat capacity
T_{01}	Fluid initial temperature [K]
T_{02}	Fluid Final Temperature [K]
η_c	Compressor isentropic efficiency
P_{01}	Fluid initial pressure [bar]
P_{02}	Fluid Final pressure [bar]
ρ_f	Fluid density [kg/m^3]
$\dot{V}_f$	Volumetric flow rate [m^3/s]
$\dot{h}$	Rate of change of Fluid level High [m/s]
A	Cross sectional Area of the tank [m^2]
r	Tank radius [m]
Δh	Change of Fluid level High [m]
h_d	The desired fluid level height [m]
Δt	Time interval length time to fill tank to the desired height [h]
$e(t)$	Error in height [m]
K_c	Proportional Gain
$u(t)$	Processed variable
t_i	Integral time [min]
t_d	Derivative time [min]

Conflicts of Interest: The authors declare no conflict of interest.

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