WATER PRESSURE LOSS ANALYSIS OF MOBILE MACHINE FOR FIRE FIGHTING PURPOSE

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Abstract—Fire fighting is risky profession. They are not only extinguishing fires in tall buildings but also must drag heavy hoses, climb high ladders and carry people from buildings and other situations. There are many fire fighters lost their lives in the line of duty each year throughout the world. The statistics of the fire fighter fatalities are still maintain at high level every year and it may continue to increase if there is no improvement in fire fighting techniques and technology. The paper describes the water pressure loss analysis of mobile fire fighting machine prototype.

Index Terms— Fire Fighting, Mobile Machine, Pressure Loss Analysis.

I. INTRODUCTION

Fire fighter need to work in a long and irregular hours and unfriendly working environment such as high temperature, dusty and low humidity, firefighters are also facing with potentially life threatening situation such as explosion, collapsed building and radioactive. The common equipment used by firefighters such as flat head axe, halligan bar, turnout jacket, fire retardant or bunker pants, boots, flashlight, helmet, face mask, and gloves do not significantly reduce risk on their lives when facing those life threatening situations.

In the USA, the traumatic death rate amongst firefighters shows that 1.9 firefighters are killed per year, per 100,000 structure fires which is the rate only slightly lower than that obtained in the early 1980s [1] . However, this rate was increasing to 3.0 per 100,000 structure fires across a thirty year period which is peaking in the 1990s [2]. There are many causes for Line of Duty Deaths (LODD) such as smoke inhalation, burns, crushing injuries and related trauma [3]. As a result of this, over the past few years, research and development on firefighting technology is extensively made around the world especially in US, Japan, and a number of European companies. There were many studies [4-8] had emphasized on machine development to replace fire fighter to fight fire in dangerous situations and to reduce the fire fighter risk. The machines help the fire fighter using extinguishing agent such as water, foam or others without fire fighter having to set up or operate directly in danger areas.

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Amano [9] highlighted the weaknesses of existing machine design and suggest integration of all important elements in developing fire fighting machine so that a successful rescuing process can be achieved. These elements are size, weight, cost and performance. Therefore, this research was integrated required technical aspects to develop a mobile machine based on the end user requirements which is fire fighting rescue team. The paper describes the water pressure loss analysis of the developed fire fighting machine (FFM).

II. CONTROL SYSTEM

The developed prototype is a mobile fire fighting machine that can be controlled wirelessly via mobile computer. Therefore, special dedicated software is developed in order to interface the machine and the computer. Additional control mechanism is added by integrating the system with a joystick in order to ensure the mobility control can be improved. Figure 1 shows the control system of FFM. Visual Basic Programming language is used in the development of the program that interfaces the machine with computer. Two way communication also possible between the victim in the fire ground and the machine operator as there is internal microphone integrated with the system. Figure 2 shows the machine and its controller which is a mobile computer and a joystick attached to the computer.
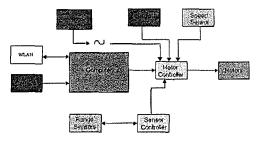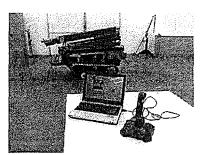

Figure 1: The control system

Figure 2: Controller and FFM

The developed FFM as shown in Figure 3 and the general specification as shown in Table 1.

Figure 3: The FFM prototype

Table 1: General specification of FFM

Item	Description
Track System	Heavy duty rubber track belt
Electrical	22V
Engine	Electric DC Motor by Sanpo Electric Co. LTD.
Engine Power	750 W
Engine Current	46 A
Engine Speed	1900 rpm or 198.97 rad/s
Torque	3.77 Nm
Transmission	2 speed. Manually changed.
Curb weight	910 kg
Maximum Speed	2.36 Km/h

III. DESIGN ANALYSIS

The engineering design analysis is conducted on the structure of the FFM in order to ensure its reliability to withstand the load experienced during operation. As water is projected from a nozzle to form a 'jet' or fire fighting stream, the nozzle tends to recoil in the opposite direction. Therefore, it is essential to counter the hose nozzle reactive force generated during fire fighting process. Manual calculation and computer aided engineering software utilizing Finite element analysis is applied in the study. Analysis made consider the maximum load applied on the machine and the maximum water pressure experienced by the machine during operation. Calculation made is to check the stability of the machine when the machine is in use.

Computer Aided Engineering (CAE) and design optimization is becoming more crucial in modern engineering design. It is because it applies numerical techniques to engineering systems in order to assist the engineering designers. This approach will be useful in improving the system's performance, weight, reliability, and/or cost.

CAE analysis and optimization methodologies can be applied during the product development stage to ensure that the finished design will have the high performance, high reliability, low weight, and/or low cost. Alternatively, design optimization methods can also be applied to existing products to identify potential design improvements. In the study, two types of design optimization being performed; namely structural design optimization and product design for assembly optimization using Boothroyd Dewhurst Method.

After completing design analysis, the prototype fabrication of the FFM proceeded. The prototype produced is a full scale prototype.

IV. PRESSURE LOSS ANALYSIS

i) Pressure Loss through Hose and Height

During operation, Pressure loss is a term used to describe the decrease in pressure from one point in a tube or hose to another point downstream. The importance of pressure loss analysis has been highlighted by many authors [10-14]. Pressure drop is the result of frictional forces on the fluid as it flows through the hose. The frictional forces are caused by a resistance to flow. However, the increase of height at the exit of flow will also cause loss of pressure. Figure 4 shows the schematic of pressure loss factor. In determining the pressure loss, Bernoulli's equation is used.
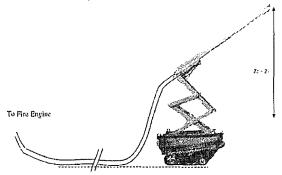

Figure 4: Pressure loss due to hose length and height

Bernoulli Principle which relates pressure, velocity and elevation between two points in flow field is applied. Assumption made using the principle is the flow is steady, incompressible, irrotational and nonviscous. The following formula is used in Fire and Rescue Department.

$$EP = NP + FL_{Hose} + FL_{Appliance} \pm P_{Elevation} \qquad (1)$$

Where,
EP = Engine Pressure
NP = Nozzle Pressure
FL_{Hose} = Friction Loss in the fire hose
$FL_{Appliance}$ = Friction Loss in the appliance
$P_{Elevation}$ = Pressure loss or gain due to elevation

Based on Manual of Firemanship Book 7: Hydraulics, pumps and pump operation, the Friction loss occur in fire hose. The friction loss is a function of hose diameter, hose length, discharge volume any appliance used such as wyes or monitors used in the hose layout. The basic of calculation in fire hydraulic revolves around three fundamental hydraulic principles namely, Bernoulli's Equation, Darcy-Weibach Equation and Continuity Equation. Friction Loss Formula as given in Equation (4.1) is derived from these three basic equations.

Friction loss in the hose, FL_{Hose} is given by a Friction Loss Equation as below [18]

$$FL_{Hose} = CQ^2L \qquad (2)$$

Where,

FL = friction loss (expressed in psi)
C = coefficient of friction
Q = flow rate in hundreds of gallons (gpm/100)
L = Length of hose in hundreds of feet (L/100)

Based on Bernoulli's equation, it is given that:

$$P_1 + \rho g z_1 + \frac{1}{2}\rho V_1^2 = P_2 + \rho g z_2 + \frac{1}{2}\rho V_2^2 + FL \qquad (3)$$

Where,

P = Pressure
ρ = Fluid density
g = Gravity
Z = Height
V = Fluid velocity
h_f = Friction losses

Whereas based on Continuity equation, it is known that:

$$Q = A_1 V_1 = A_2 V_2 \qquad (4)$$

Where,

Q = Volume flow rate
A = Cross section area
V = Fluid velocity

ii) Nozzle Force

In analyzing force at nozzle of FFM, the system can be considered as a thermodynamic system that has an open system or control volume and involves the flow of fluid through the fix volume. As fluid moves through the control volume, the mass entering the control volume is equal to the mass leaving the control volume. The surface enclosing the control volume is referred to as the control surface. The force at nozzle is determined with information such as, maximum water pressure and nozzle dimension using Bernoulli's equation and momentum equation. The component involve in the force determination of the nozzle as shown in Figure 5.
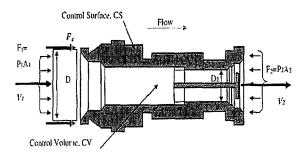

Figure 5: Cross sectional view of water nozzle

The water inlet and outlet velocity V_1 and V_2 can be obtained by solving Continuity Equation.

$$V_1 = \frac{Q}{A_1} = \frac{4Q}{\pi D_1^2} \qquad (5)$$

Based on the Friction Loss, the Nozzle Pressure can be calculated based on the following formula. (Referring to NFPA 1002 Standard of Fire Apparatus Driver/Operator Profesional Qualifications)

$$EP = NP + FL_{Hose} + FL_{Appliance} \pm P_{Elevation} \qquad (6)$$

V. RESULTS

iii) Pressure Loss through Hose and Height

Flow rate, Q_2 = $V_2 A_2$
= 629.257 gpm

Therefore, Friction Loss is

$$FL = 0.00065 V_2^2 = 1.399 \text{ kPa}$$

Based on the Friction Loss, the Nozzle Pressure can be calculated based on the following formula.

$$NP = 11.64 \text{ bar}$$

5.2 Nozzle Force

For, D_1=0.0635m, D_2 = 0.03302m, Q =0.0397 $m^3 s^{-1}$, the water inlet and outlet velocity V_1 and V_2 obtained by solving Continuity Equation.

$$V_1 = \frac{Q}{A_1} = \frac{4Q}{\pi D_1^2} = 12.53 \, ms^{-1}$$

$$V_2 = \frac{Q}{A_2} = \frac{4Q}{\pi D_2^2} = 46.36 \, ms^{-1}$$

Based on the Friction Loss, the Nozzle Pressure can be calculated based on the following formula.

$$NP = EP - FL_{Hose} - FL_{Appliance} \pm P_{Elevation} = 11.64 \text{ bar}$$

Bernoulli's Momentum equation is used to determine the force, F_{nozzle}, required to hold the nozzle in it position.

$$F_{nozzle} = \rho Q(V_2 - V_1) - P_1 A_1 + P_2 A_2 = -2,257 \, N$$

Therefore the nozzle reaction force or minimum force required to hold the nozzle is 2.257 N.

VI. CONCLUSION

In this paper, the pressure loss of nozzle and nozzle force has been analyzed. Three fundamental hydraulic principles were used to analyze the nozzle, namely, Bernoulli's Equation, Darcy-Weibach Equation and Continuity Equation. Based on the calculation, total pressure loss of nozzle is 11.64 bar. For the nozzle force, the nozzle reaction force to hold the nozzle is 2257 N.

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