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MODELING AND OPTIMIZATION OF WATER-JET TRANSPORT PHENOMENON IN FIRE SERVICE

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ABSTRACT

A model is developed that will allow the fireman to stand as far back as possible from a collapsing wall of a storey building while directing a water jet into a window of the burning building. The variables in the model are therefore, the initial angle (**α**) and the distance of the fireman from the wall (x). Data collected from Imo State Fire Service, Nigeria, were used in validating the model. The model gives 60^o as an optimum initial water jet angle to the horizontal. With 60^o as the initial angle, the optimum distance is dependent on the initial velocity of the gun. This can be applied in a burning storey building that is in the risk of collapsing anywhere in the world. The optimum distance from the wall must satisfy equation (10). The work enables the fireman to know a particular point to stand near the building with respect to initial velocity of water fountain and its initial tilt to the horizontal.

KEYWORDS: Modeling, Optimization, Water-Jet, Fire Service, Burning, Collapsing Building.

INTRODUCTION

There have been a lot of fire disasters with firemen almost everywhere. For example, the fire outbreak which burnt down the building housing the United Bank of Africa (UBA) along Douglas Road in Owerri Imo-State. The fire began and lasted till the following morning, although firemen from Imo State Fire Service came to the scene.

The possibility of fire outbreak in buildings all over the country has made this study very important, more so, the fire service men are still ill-equipped or do not have enough aerodynamic knowledge for putting off fire (Hewson *et al*., 2004, Abbott, 1971). This study lends credence to the mastery of fire service to the firemen.

The objective of this study is to model a projectile of water fountain trajectory onto a burning story building and to optimize the distance of the firemen from the building with respect to initial angle of the water-jet to horizontal. This will enable the fireman to know a particular point to stand near the building with respect to initial velocity of water fountain and its initial tilt to the horizontal.It does not cover the final angle of entry of the water-jet to the window, the size of window, the spread of the water jet or air resistance acting on the water flow.

MODEL DEVELOPMENT

A fireman is directing a jet of water into a window of burning storey building. Owing to the heat, and the danger of the walls collapsing, the fireman wishes to stand as far back as possible while still being able to direct the water jet through the window as shown in ***fig. 1.***

Some assumptions are made for this modeling (Kamalu, 2010, Edward and Hamson, 2009):

- the water jet is effectively a stream of particles
- air resistance, cross wind changes in water pressure etc are neglected.
- the size of the window is neglected in this model.

Fig.1 shows the forces acting on the water trajectory. There will be two equations of motion; one of this will represent the horizontal motion and the other vertical motion. Newton's second law can be applied in each direction separately and in doing so we get a pair of uncoupled equations i.e. the dependent variables do not appear in both equations (Edward and Hamson, 2009; Ollerenshaw, 2005). This uncoupled nature of the equations will help us to obtain the solution of the model. Newton's second law states that force = mass x acceleration for the horizontal motion.

The two components of forces acting on water jet are (Kamalu, 2010):

Horizontal: FR = max
Vertical : FR –Fg = may

where FR = frictional force on water jet in the air which is assume to be zero.

Noting that ax = $\frac{d^2x}{dt^2}$ and ay = $\frac{d^2y}{dt^2}$ and that Fg = mg where m = elemental mass of water-jet, we have,

$$0 = m\frac{d^2x}{dt^2} \quad (1)$$

and for the vertical motion,

$$0 - mg = m\frac{d^2y}{dt^2} \quad (2)$$

We can imagine a small group of droplets sufficiently closed to be taken together as a particle of mass (m). The jet of water can be regarded as a stream of such particles (Pushpavanam 2005, Edward and Hamson, 2009). The point about uncoupled nature of the equations can be seen in equation (1) & (2), since the dependent variables are x & y.

MATHEMATICAL MODEL SOLUTION

Straight integration of equation (1) twice will give

$$x = C1t + C2$$

At t =0, and x = 0, C2 = 0

$$\text{Or } x = C1t \quad (i)$$

for equation (2), $\frac{dy}{dt} = - gt + C3$

or $y = -\frac{gt^2}{2} + C3t + C4$

At t = 0, y = h (height of the fireman)

$$y = - \tfrac{1}{2} gt^2 + C3t + h \quad (ii)$$

It will be seen that C1 in (i) and C3 in (ii) are components of initial jet velocity (u) in x and y – directions i.e. u cos$\boldsymbol{\alpha}$ and u sin$\boldsymbol{\alpha}$ respectively. Thus, reintroducing them into (i) and (ii) yield (Kamalu, 2010, Edward and Hamson, 2009).

$$x = ut\cos\boldsymbol{\alpha} \quad (3)$$

$$y = ut\sin\boldsymbol{\alpha} - \tfrac{1}{2} gt^2 + h \quad (4)$$

This is how far away the fireman can stand and still direct his jet through the window. A moment through tells that we are not really interested in how long it takes the water jet to reach its destination, but are concerned with distances and angles involved. (Anyone in the burning storey building wishing to be rescued certainly will be interested in how long the water jet takes to arrive, but that is rather different (Razdolsky, 2009, Baum et al, 1994)).

Eliminating time (t) in equations (3) and (4) yields

$$y = \frac{x\tan\alpha - gx^2}{2u^2 Cos^2\alpha} + h \quad (5)$$

The jet passes through a point (x, y) or (D, H) so that the model can be written as

$$H = \frac{D\tan\alpha - gD^2}{2u^2 cos^2\alpha} \quad (6)$$

OPTIMIZATION OF MODEL

In equation (5), y, h, g and u are all fixed so that x is the variable to be optimized over changing $\boldsymbol{\alpha}$. Regarding $\boldsymbol{\alpha}$ as a continuous variable we can differentiate in the usual way (Kamalu, 2010, Edward and Hamson, 2009) and put:

$$\frac{dx}{d\alpha} = 0 \quad \text{(Stroud, 2001)}$$

which yields $u^2/g = Xm \tan\boldsymbol{\alpha}m$ (7)

(See Appendix A for full solution)

The optimum values sought are Xm = Dm and $\boldsymbol{\alpha}$ = $\boldsymbol{\alpha}$m with equation (7) as the optimum equation. After some manipulation (see Appendix B), the mathematical solutions of the model are given as;

$$\text{Sin}^2\,\boldsymbol{\alpha}m = \frac{u^2}{2[u^2 - g\,(H-h)]} \quad (8)$$

$$Dm = \frac{u\sqrt{u^2 - 2g\,(H-h)}}{g} \quad (9)$$

Note: that equation (9) is valid only for

$$u^2 > 2g\,(H\text{-}h) \quad (10)$$

COLLECTION OF DATA

Imo State fire services station headquarters was visited. A roaster for different initial angles ($\boldsymbol{\alpha}$) of the gun of water jet shows that any angle is possible between 10^o to 90^o and any initial velocity of water-jet (10 to 50 m/s) is possible. This knowledge was used in computing the optimum distance with different initial velocities using equation (7). The results are shown in table 1.

Computations and Plots

The collected data were used in computing Table 1, when distances are plotted against initial angles for each velocity, the graph of fig 2 results, showing water-jet initial tilt angle ($\boldsymbol{\alpha}$), velocity (u) and optimum distance from the wall of the burning building (Kamalu, 2010).

RESULTS

The results of the calculation and plots in section 4.2 are shown below;

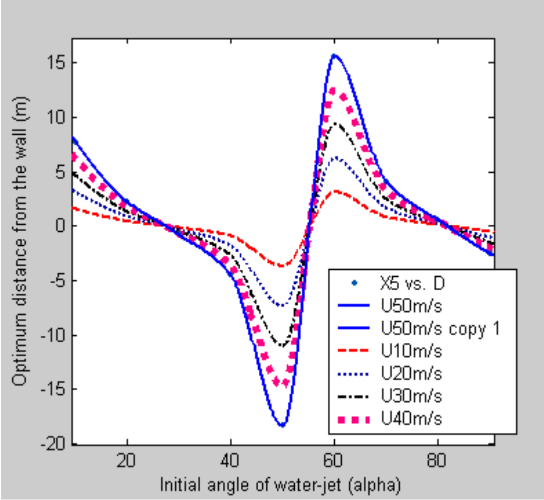

Fig. 1; Optimum distance of fireman from the wall versus Optimum initial angle of water-jet for different initial water-jet velocities

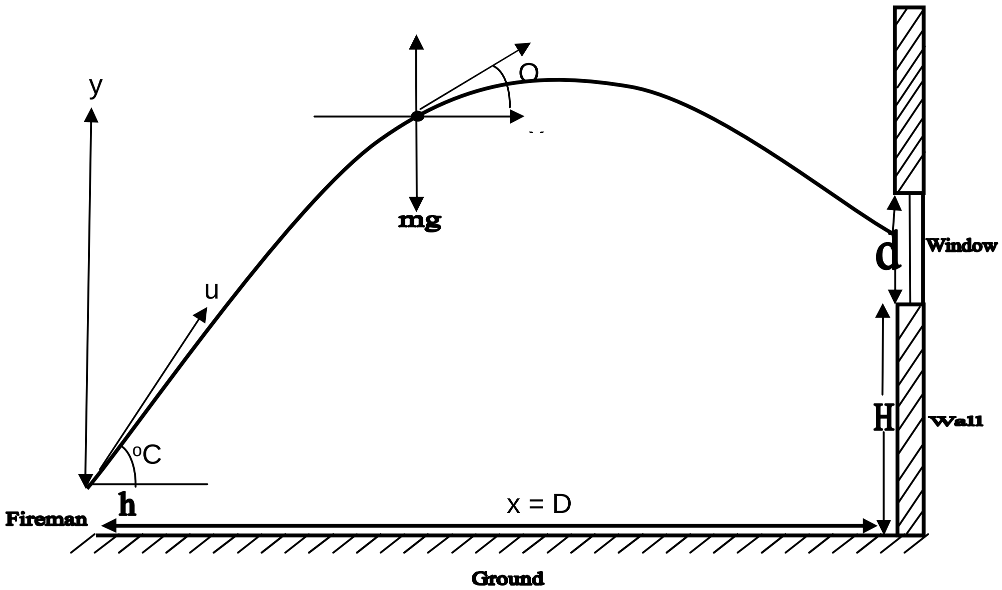

Fig 1

Fig. 2: A jet of water into a window of a Burning Storey Building

Table 1: Computed values using equation (7)

Um/s	α	10	20	30	40	50	60	70	80	90
10m/s	X1	1.5424	0.4470	-0.1561	-0.895	-3.6778	3.1246	0.8184	0.1111	-0.5012
20 m/s	X2	3.0847	0.894	-0.3122	-1.7902	-73556	6.2492	1.6367	0.2221	-1.0024
30 m/s	X3	4.6271	1.3410	-0.4684	-2.6852	-11.0334	9.3738	2.4551	0.3332	-1.5036
40 m/s	X4	6.1694	1.7880	-0.6245	-3.5803	-14.7113	12.4984	3.2734	0.4443	-2.0048
50 m/s	X5	7.7118	2.2350	-0.7806	-4.4754	-18.3891	15.6230	4.0918	0.5553	-2.5060

DISCUSSION

From table 1 and fig 1 it can be seen that optimum initial angle for a fireman to set his gun is 60^o for a particular velocity and optimum distance of the fireman from the wall. The optimum model, therefore, is equation (7) which allows the fireman to stand as far as back as possible from the wall of the storey building. Hence, keeping optimum tilt initial angle at 60^o, choice variation between optimum fireman distance from the wall and initial water-jet velocity can be made in Fig. 1.

CONCLUSION

A Models is developed that will allow the fireman to stand as far back as possible from a collapsing wall of a storey building while directing a water jet into a window of the burning building. The variables in the models are, therefore, the initial angle ($\boldsymbol{\alpha}$) and the distance of the fireman from the wall (x).

Data collected from Imo State Fire Service, Nigeria were used in validating the models. The model gives 60^0 as an optimum initial water jet angle to the horizontal. With 60^0 as the initial angle, the optimum distance is dependent on the initial velocity of the gun. This can be applied in a burning storey building that is in the risk of collapsing anywhere in the world. The optimum initial angle and the optimum distance from the wall must satisfy equation (10).

LIMITATIONS

Air resistance to water flow, the angle at which the water jet enters the window and the size of the windows were not considered.

RECOMMENDATION

The angle at which the water jet enters the window, the size of the window and air resistance on the water flow should be considered in further work.

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APPENDIX A: DERIVATION OF OPTIMUM MODEL

$$y = x\tan\alpha - \frac{gx^2}{2u^2\cos^2\alpha} + h \qquad \text{--------------------- (A1)}$$

Differentiating x w.r.t α and equate to zero i.e. $\frac{dx}{d\alpha} = 0$, (Stroud 2001).

$$0 = \tan\alpha \frac{dx}{d\alpha} + x d(\tan\alpha) - \frac{(2u^2\cos^2\alpha) .\ 2gx\ \frac{dx}{d\alpha}\ - gx^2 .\ 2u^2 d(\cos^2\alpha)}{(2u^2\cos^2\alpha)^2} .$$

$$\tan\alpha \frac{dx}{d\alpha} + x\sec^2\alpha = \frac{4u^2 g\cos^2\alpha . x\frac{dx}{d\alpha} - 2u^2 gx^2(-2\cos\alpha\sin\alpha)}{4u^4\cos^4\alpha}$$

$$4u^4 \tan\alpha \cos^4\alpha \frac{dx}{d\alpha} + 4u^4\cos^4\alpha . x \sec^2\alpha = 4u^2 g\cos^2\alpha . x \frac{dx}{d\alpha} + 4u^2 g x^2 \cos\alpha \mathrm{Sin}\alpha$$

$$4u^2\cos^2\alpha(U^2\tan\alpha\ \cos^2 - gx)\frac{dx}{d\alpha} = 4\ x\ u^2\cos\alpha(gx\mathrm{Sin}\alpha - u^2\cos^3\alpha\sec^2\alpha)$$

$$\frac{dx}{d\alpha} = 0 = \frac{x(gx\mathrm{Sin}\alpha - u^2\cos^3\alpha\sec^2\alpha)}{\cos\alpha(u^2\tan\alpha\cos^2\alpha - gx)}$$

$$x(gx\sin\alpha - u^2\cos^3\alpha\sec^2\alpha) = 0 .$$

$$x = 0, or\ x = \frac{u^2}{g}\frac{\cos^3\alpha\sec^2\alpha}{\mathrm{Sin}\alpha},\ but\ \sec\alpha = \frac{1}{\cos\alpha}$$

$$x = \frac{u^2}{g}\frac{\cos\alpha}{\mathrm{Sin}\alpha} = \frac{u^2}{g\tan\alpha}$$

$$\frac{u^2}{g} = x\tan\alpha \qquad \text{---------------------------- A2}$$

APPENDIX B: DERIVATION OF THE OPTIMUM VARIABLE PARAMETERS

When x = D, y = H and substituting equation (A2) into equation (A1) yields

$$H-h=D.\frac{u^2}{gD}-\frac{g\left(\frac{u^2}{g\tan\alpha}\right)^2}{2u^2\cos^2\alpha}=\frac{u^2}{g}-\frac{\frac{u^4}{g}\cdot\frac{\cos^2\alpha}{Sin^2\alpha}}{2.u^2\cos^2\alpha}=\frac{u^2}{g}-\frac{u^2}{2g\sin^2\alpha}$$

$$=\frac{u^2}{g}\left(1-\frac{1}{2Sin^2\alpha}\right)$$

$$(H-h)g=u^2-\frac{u^2}{2Sin^2\alpha}$$

$$Sin^2\alpha=\frac{u^2}{2\left[u^2-(H-h)g\right]} \quad \text{--------------------------} \quad \text{(A3)}$$

Substituting equation (A2) into equation (A1) for $\tan\alpha$ and $x = D,\ y = H$

$$H-h=D.\frac{u^2}{gD}-\frac{gD^2}{2u^2\cos^2\alpha}=\frac{u^2}{g}-\frac{gD^2}{2u^2\cos^2\alpha}$$

$$2u^2\cos^2\alpha=\frac{g^2D^2}{u^2-(H-h)g}, \qquad \cos^2\alpha=\frac{g^2D^2}{2u^2\left[u^2-(H-h)g\right]} \quad \text{.......} \quad \text{(A4)}$$

But $Sin^2\alpha + \cos^2\alpha = 1$

From equations (A3) and (A4)

$$\frac{g^2D^2}{2u^2\left[u^2-(H-h)g\right]}+\frac{u^2}{2\left[u^2-(H-h)g\right]}=1$$

If $\theta=(H-h)g$,

$$\frac{g^2D^2}{2u^2\left[u^2-\theta\right]}+\frac{u^2}{2\left[u^2-\theta\right]}=1$$

$$\frac{g^2D^2+u^4}{2u^2\left[u^2-\theta\right]}=1$$

$$g^2D^2+u^4=2u^2\left[u^2-\theta\right]$$

$$g^2D^2=-u^4+2u^4-2u^2\theta=u^4-2u^2\theta=u^2(u^2-2\theta)$$

$$D=\frac{u}{g}\sqrt{u^2-2\theta}=\frac{u}{g}\sqrt{u^2-2(H-h)g} \quad \text{---------------} \quad \text{(A5)}$$

$$i.e.\ u^2-2(H-h)g>O \quad \text{--------------------------------} \quad \text{(A6)}$$