Novel Approaches to Fast Filling of Hydrogen Cylinders

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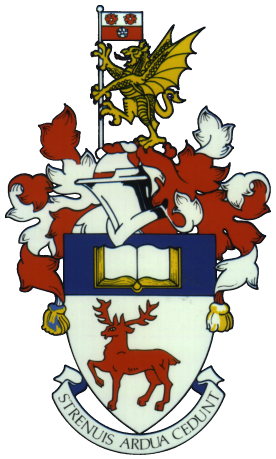

This report is submitted in partial fulfillment of the requirements for the MEng Mechanical Engineering, Faculty of Engineering and the Environment, University of Southampton.

Declaration

I, Pau Miquel Mir, declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

1. This work was done wholly or mainly while in candidature for a degree at this University;
2. Where any part of this thesis has previously been submitted for any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. None of this work has been published before submission.

Acknowledgements

I want to thank my advisor for his time and dedication.
I also want to thank my parents, for their constant support and for proofreading the paper.

Abstract

This is the abstract.

Contents

Acronyms

ABS Anti-lock Braking System

SVM Support Vector Machine

1 Introduction

Hydrogen is a very promising alternative fuel for the future, mainly due to the absence of greenhouse emissions when burning it. There are however several concerns with hydrogen fuels, such as: risk of carried compressed fuel, obtaining hydrogen itself, etc. However, one of the most important aspects is the convenience and user experience. Indeed, even if a new technology is scientifically better, consumers will prefer an inferior technology that is more convenient to them, especially if the improved technology doesn?t directly affect them (as reduced emissions don?t). For this reason, it is essential for the success of hydrogen as a fuel for its use to be as ? if not more ? convenient than traditional fuel. One of the main aspect?s that currently lags behind traditional fuel is the refueling experience. Given that refueling hydrogen involves its compression, there is a significant rise in temperature, which must be kept below certain standards (358K as per SAE J2601). This in turn leads to long refueling times, potentially lasting more than five minutes, which is cumbersome for users. Therefore, it is of prime importance to research and develop systems that enable the faster refueling of hydrogen cylinders. To this end, this project will build upon a model of filling a hydrogen cylinder which has already been developed by members of the department.

One of the current solutions to improve fill times involves cooling the hydrogen before filling the cylinder as to keep it below he maximum temperature. However, this is quite expensive, both in energy terms and in economic terms. Consequently, the aim of this project is to continue exploring several of the options available to reduce fill times and simultaneously reduce the energy consumption of the process, thus improving both convenience for users and energy efficiency of the fueling stations. Indeed, by building upon the existing cylinder model several options shall be considered, namely: refrigeration, flow regulation, heat sink usage, active cooling, heat pipe usage, phase change materials, etc. From here, several options are open to further deepen or potentially broaden the investigation. An attempt to further simplify the model can be made, perhaps even reducing it so a simple algebraic relationship. Also, the model would benefit from FEA validation to aid our understanding of the heat transfer in the structure. This would go hand in hand with analyzing the temperature of the structure, and see how close this matches the gas temperature. Indeed, if the structure is at a much lower temperature than the gas, the case can be made that the current regulations are slightly erroneous, as they are meant to protect the materials of the structure, but instead regulate the gas temperature.

2 Conclusion

This is the conclusion. This is shit. This is crap. Fuck fuck this is boring.

Appendices

A Prova

This is a new Appendix.

$$3+3=6 \tag{A.1}$$

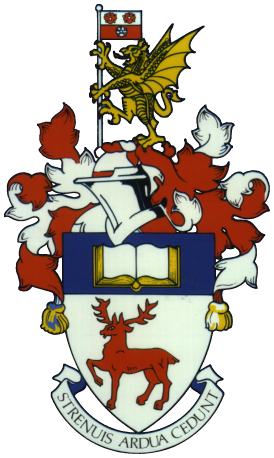

FIGURE A.1: Prova

1. Title page pretty

2. Word count glossaries

A.1 Proves

First use: Support Vector Machine (SVM). Second use: SVM.

First use: Anti-lock Braking System (ABS). Second use: ABS.

Prova [1]. Also, here is a trial on Fig. A.2

This is a piece of shit. Fuck Prova merda I just keep on typing and want to see what happens, there is simply a bit of a lag and that it and that's it, shit this isn't working. It is, it is simply very very slow. I want to see if I can keep on typing and see what happens, it is quite nice indeed. How many words can I get without it working this is pretty cool and now I want to in insert a reference to Fig A.2 This is interesting. What if I want to [1], and also [2], finally **Nelder1965**

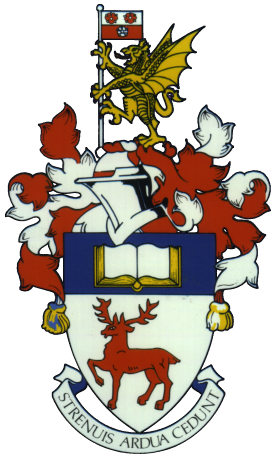

FIGURE A.2: This caption is really really long and uses up more than one line to test the caption package to see what the fuck happens. This is a test. Caca.

In Fig. A.2 we can see a shitty coat of arms. I am going to add eight more words. afjhffa

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{A.2}$$

1	0	0	0	0
0	1	0	0	0
0	0	1	0	0
0	0	0	1	0
0	0	0	0	1

B Eurobot Code

```
%Author: Vishagen Ramasamy
%Date: -

% Copyright University of Southampton 2017.
% No warranty either expressed or implied is given to the results produced
% by this software.  Neither the University, students or its employees
%accept any responsibility for use of or reliance on results produced by
%this software.

%% script that computes the filling of the tank(s)
%% Importing the pressure and temperature profile at the entrance of the delivery pipe from Dicken a
%  and calulating the stagnation enthalpy and entropy

for j = 1:maxt
    time(j+1) = (j)*dt;                                                    % Time as filling proce
    for i = 1:tank_number
        % Select inlet pressure / temperature profile based on user input
        if blnUseStandardData == 1
```

```
19              % Constant inlet pressure profile
20              P_inlet(i,j+1) = ConstPressKPa;
21          else
22              % Read inlet pressure profile from specified file
23              P_inlet(i, j+1) = interp1(InletPressureData(:,1),InletPressureData(:,3), dt*j);
24          end
25
26          if blnUseStandardData == 1
27              %Temp_inlet(i,j+1) = interp1(time_in, temp_in, dt*j);   % Temperature profile after the first 1.35 s
28              Temp_inlet(i, j+1) = ConstTempK;
29          else
30              % Read inlet temperature profile from specified file
31              Temp_inlet(i, j+1) = interp1(InletTempData(:,1), InletTempData(:,3), dt*j);
32          end
33
34          h_inlet(i,j+1) = refpropm('H','T',Temp_inlet(i,j+1),'P',P_inlet(i,j+1),Fluid{i}, refpropdir);       % Re
35          entropy_inlet(i,j+1) = refpropm('S','T',Temp_inlet(i,j+1),'P',P_inlet(i,j+1),Fluid{i}, refpropdir); % Re
36
37          %% Determine which pressure to use at the exit of the delivery pipe which is dependent upon the number o
38
39          if l_d(i) > 3 && blnOneZone{i} == 0          % The length-to-diameter ratio of the tank(s) determines th
40              Pressure_exit = P_gas_zone1{i}(j);   % The pressure at the exit of the delivery pipe is equal to the
41          else
42              Pressure_exit = P_gas(i,j);          % The pressure at the exit of the delivery pipe is equal to the
43          end
44
45          if (P_inlet(i,j+1) > Pressure_exit)  % condition for filling of tank(s)
46              sound_exit(i,j+1) = refpropm('A','P',Pressure_exit,'S',entropy_inlet(i,j+1),Fluid{i}, refpropdir);
47              h_static_exit(i,j+1) = refpropm('H','P',Pressure_exit,'S',entropy_inlet(i,j+1),Fluid{i}, refpropdir)
48              visc_exit(i,j+1) = refpropm('V','P',Pressure_exit,'S',entropy_inlet(i,j+1),Fluid{i}, refpropdir);
49              mach_exit(i,j+1) = sqrt(2*(h_inlet(i,j+1)-h_static_exit(i,j+1))/sound_exit(i,j+1)^2);   % Calculates
50
51              %% If Mach number is greater than one, the exit pressure is greater than the pressure within the tan
52              %  is incremetally increased and iterated in a while loop  until mach number is equal to one
53
54              Inlet_entropy = entropy_inlet(i,j+1);
55              Inlet_stagnation_enthalpy = h_inlet(i,j+1);
56              P_guess =  Pressure_exit;
57
58              if mach_exit(i,j+1) > 1
59                  Pressure_exit = find_exit_pressure(Inlet_stagnation_enthalpy,Inlet_entropy,Fluid{i},P_guess, ref
60                  sound_exit(i,j+1) = refpropm('A','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, refpropdir);
61                  h_static_exit(i,j+1) = refpropm('H','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, refpropdir);
62                  visc_exit(i,j+1) = refpropm('V','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, refpropdir);
63                  mach_exit(i,j+1) = sqrt(2*(h_inlet(i,j+1)-h_static_exit(i,j+1))/sound_exit(i,j+1)^2);       % Co
64              end
65
66              %% Calculation of the mass flow rate into the tank(s)
67
68              rho_exit(i,j+1) = refpropm('D','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, refpropdir);
69              vel_exit(i,j+1) = mach_exit(i,j+1)*sound_exit(i,j+1);                                          % Calcul
70              Re_exit_isentropic(i,j+1) = rho_exit(i,j+1) *d_inlet*vel_exit(i,j+1)/visc_exit(i,j+1);         % Calcul
71              cd(i,j+1) =  I + J/(Re_exit_isentropic(i,j+1)^(0.25));                                         % Calcul
72              mfr(i,j+1) = cd(i,j+1)*rho_exit(i,j+1)*vel_exit(i,j+1)*A_inlet;                                % Calcul
73              Re_entrance_actual(i,j+1)= 4*mfr(i,j+1)/(pi*d_inlet*visc_exit(i,j+1));                         % Calcul
74              dM_inlet = mfr(i,j+1)*dt;                                                                      % Amount
75          end
76
77          %% Heat transfer calculations & caluclations of the thermodynamic properties of the gas in the tank(s) w
78          if l_d(i) <= 3 | blnOneZone{i} == 1
79
80              Nus(i,j+1) =   a_1*Re_entrance_actual(i,j+1)^(b_1);                  % Nusselt number and Reynolds
81              k_gas(i,j+1) = refpropm('L','T',Temp_gas(i,j),'P',P_gas(i,j),Fluid{i}, refpropdir);  % Thermal condu
82              heat_coef_forced(i,j+1) = Nus(i,j+1)*k_gas(i,j+1)/d_tank(i);         % Calculation of the heat tran
83
84              if Inner_wall_boundary(i) == 1
```

```
85                  Qsurf(i,j+1) = -dt*surf_area(i)*heat_coef_forced(i,j+1)*(Temp_gas(i,j)-Inner_temp_wa
86              else
87                  Qsurf(i,j+1) = -dt*surf_area(i)*heat_coef_forced(i,j+1)*(Temp_gas(i,j)-Temp_wall{i}(
88                  Temp_wall{i}(1,j+1) = Temp_wall{i}(1,j)+ CFL_liner(i)*(Temp_wall{i}(2,j)- Temp_wall{
89
90                  if Outer_wall_boundary(i)==1
91                      Temp_wall{i}(number_of_gridpoints(i),j+1) = Outer_temp_wall_isothermal(i);
92                  else
93                      Temp_wall{i}(number_of_gridpoints(i),j+1) = Temp_wall{i}(number_of_gridpoints(i)
94                  end
95                  % Computation of the temperature of the struture of the tank(s)
96                  for k=2:number_of_gridpoints(i)-1
97                      if (k>=2)&&(k<=int_pt_liner_laminate(i)-1)
98                          Temp_wall{i}(k,j+1) = Temp_wall{i}(k,j)+CFL_liner(i)*(Temp_wall{i}(k+1,j)-2*
99                      elseif (k>=int_pt_liner_laminate(i)+1)&&(k<=number_of_gridpoints(i)-1)
100                         Temp_wall{i}(k,j+1) = Temp_wall{i}(k,j)+CFL_laminate(i)*(Temp_wall{i}(k+1,j)
101                     else
102                         Temp_wall{i}(k,j+1) = (cond_laminate(i)*(Temp_wall{i}(k+1,j)+CFL_laminate(i)
103                     end
104                 end
105             end
106             m_gas(i,j+1) = m_gas(i,j)+ dM_inlet;                                                    % Mas
107             Ugas(i,j+1)=Ugas(i,j)+Qsurf(i,j+1)+h_inlet(i,j+1)*dM_inlet;                             % Int
108             u_gas(i,j+1)= Ugas(i,j+1)/m_gas(i,j+1);                                                 % Spe
109             rho_gas(i,j+1)=m_gas(i,j+1)/vol_tank(i);                                                % Den
110             P_gas(i,j+1) = refpropm('P','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir);
111             Temp_gas(i,j+1) = refpropm('T','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir)
112
113         else
114             Re_compression(i,j+1) = Re_entrance_actual(i,j+1)*(d_inlet/d_tank(i));                  % Rey
115
116             Nus_zone1{i}(j+1) =  a_1*Re_entrance_actual(i,j+1)^(b_1);                               % Nus
117             Nus_zone2{i}(j+1) =  c_1*Re_compression(i,j+1)^(d_1);                                   % Nus
118
119             k_gas_zone1{i}(j+1) =  refpropm('L','T',Temp_gas_zone1{i}(j),'P',P_gas_zone1{i}(j),Fluid
120             k_gas_zone2{i}(j+1) =  refpropm('L','T',Temp_gas_zone2{i}(j),'P',P_gas_zone2{i}(j),Fluid
121
122             heat_coef_forced_zone1{i}(j+1) =  Nus_zone1{i}(j+1)*k_gas_zone1{i}(j+1)/d_tank(i);
123             heat_coef_forced_zone2{i}(j+1) =  Nus_zone2{i}(j+1)*k_gas_zone2{i}(j+1)/l_zone2_total(i)
124
125             % Step 1. Equating the respecting values of zone 1 and zone 2 to
126             % matrices with 'similar' names
127
128             Vgas(1)=volume_zone1(i);
129             Vgas(2)=volume_zone2(i);
130             Mgas(1)=m_gas_zone1{i}(j);
131             Mgas(2)=m_gas_zone2{i}(j);
132             Ugas_twozone(1)=u_gas_zone1{i}(j)*Mgas(1);
133             Ugas_twozone(2)=u_gas_zone2{i}(j)*Mgas(2);
134             Asurf(1)=surface_area_zone1(i);
135             Asurf(2)=surface_area_zone2(i);
136             Tgas(1)=Temp_gas_zone1{i}(j);
137             Tgas(2)=Temp_gas_zone2{i}(j);
138             if Inner_wall_boundary(i) == 1
139                 Twall(1,1)=Inner_temp_wall_isothermal(i);
140                 Twall(2,1)=Inner_temp_wall_isothermal(i);
141             else
142                 Twall(1,1)=Temp_wall_zone1{i}(1,j);
143                 Twall(2,1)=Temp_wall_zone2{i}(1,j);
144             end
145             % Step 2: apply the change of internal energy due to heat transfer and mass
146             % input through nozzle:
147
148             dM_inlet = mfr(i,j+1)*dt;
149
150             Qsurf(1)=- dt*Asurf(1)*(heat_coef_forced_zone1{i}(j+1))*(Tgas(1)-Twall(1,1));
```

```
151             Qsurf(2)=- dt*Asurf(2)*(heat_coef_forced_zone2{i}(j+1))*(Tgas(2)-Twall(2,1));
152
153             Ugas_twozone(1)=Ugas_twozone(1)+Qsurf(1)+h_inlet(i,j+1)*dM_inlet;
154             Ugas_twozone(2)=Ugas_twozone(2)+Qsurf(2);
155
156             Mgas(1)=Mgas(1)+dM_inlet;
157             Mgas(2)=Mgas(2);
158
159             for m=1:2
160                 hgas(m)=refpropm('H','D',Mgas(m)/Vgas(m),'U',Ugas_twozone(m)/Mgas(m),Fluid{i}, refpropdir);
161             end
162
163
164             % Step 2: Find the amount of mass that needs to be transferred from zone 1
165             % to zone 2 to equalise their pressure
166             % (we assume forward Euler integration, therefore we use the specific
167             % enthalpies h from the start of the timestep. We provide enthalpies for
168             % both zones in case the flow gets reversed).
169
170             dM_guess = dM_inlet*(volume_zone2(i)/(volume_zone1(i)+volume_zone2(i))) ;
171             dM_12 = find_dM_12(hgas,Vgas,Mgas,Ugas_twozone,Fluid{i},dM_guess, refpropdir);
172
173             % Step 3: Apply this change to the mass and update all properties:
174
175             m_gas_zone1{i}(j+1)=Mgas(1)-dM_12;
176             m_gas_zone2{i}(j+1)=Mgas(2)+dM_12;
177
178             u_gas_zone1{i}(j+1)=(Ugas_twozone(1)-max(0,dM_12)*hgas(1)-min(0,dM_12)*hgas(2))/m_gas_zone1{i}(j+1)
179             u_gas_zone2{i}(j+1)=(Ugas_twozone(2)+max(0,dM_12)*hgas(1)+min(0,dM_12)*hgas(2))/m_gas_zone2{i}(j+1)
180
181             rho_gas_zone1{i}(j+1)=m_gas_zone1{i}(j+1)/volume_zone1(i);
182             rho_gas_zone2{i}(j+1)=m_gas_zone2{i}(j+1)/volume_zone2(i);
183
184             Temp_gas_zone1{i}(j+1)=refpropm('T','D',rho_gas_zone1{i}(j+1),'U', u_gas_zone1{i}(j+1),Fluid{i}, ref
185             Temp_gas_zone2{i}(j+1)=refpropm('T','D',rho_gas_zone2{i}(j+1),'U', u_gas_zone2{i}(j+1),Fluid{i}, ref
186
187             P_gas_zone1{i}(j+1)=refpropm('P','D',rho_gas_zone1{i}(j+1),'U', u_gas_zone1{i}(j+1),Fluid{i}, refpro
188             P_gas_zone2{i}(j+1)=refpropm('P','D',rho_gas_zone2{i}(j+1),'U', u_gas_zone2{i}(j+1),Fluid{i}, refpro
189
190             m_gas(i,j+1) = m_gas_zone1{i}(j+1) + m_gas_zone2{i}(j+1);
191             rho_gas(i,j+1) = m_gas(i,j+1)/vol_tank(i);
192             u_gas(i,j+1)= (u_gas_zone1{i}(j+1)*m_gas_zone1{i}(j+1)+ u_gas_zone2{i}(j+1)*m_gas_zone2{i}(j+1))/m_g
193             Ugas(i,j+1) = u_gas(i,j+1)*m_gas(i,j+1);
194             Temp_gas(i,j+1)  = refpropm('T','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir);
195             P_gas(i,j+1)  = refpropm('P','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir);
196
197             if Inner_wall_boundary(i) == 1
198                 Qsurf_zone1{i}(j+1) = -dt*surface_area_zone1(i)* heat_coef_forced_zone1{i}(j+1)*(Temp_gas_zone1+
199                 Qsurf_zone2{i}(j+1) = -dt*surface_area_zone2(i)* heat_coef_forced_zone2{i}(j+1)*(Temp_gas_zone2+
200             else
201                 Qsurf_zone1{i}(j+1) = -dt*surface_area_zone1(i)* heat_coef_forced_zone1{i}(j+1)*(Temp_gas_zone1+
202                 Qsurf_zone2{i}(j+1) = -dt*surface_area_zone2(i)* heat_coef_forced_zone2{i}(j+1)*(Temp_gas_zone2+
203
204                 Temp_wall_zone1{i}(1,j+1) = Temp_wall_zone1{i}(1,j)+ CFL_liner(i)*(Temp_wall_zone1{i}(2,j)- Temp
205                 Temp_wall_zone2{i}(1,j+1) = Temp_wall_zone2{i}(1,j)+ CFL_liner(i)*(Temp_wall_zone2{i}(2,j)- Temp
206
207                 if Outer_wall_boundary(i)==1
208                     Temp_wall_zone1{i}(number_of_gridpoints(i),j+1) = Outer_temp_wall_isothermal(i);
209                     Temp_wall_zone2{i}(number_of_gridpoints(i),j+1) = Outer_temp_wall_isothermal(i);
210                 else
211                     Temp_wall_zone1{i}(number_of_gridpoints(i),j+1) = Temp_wall_zone1{i}(number_of_gridpoints(i)
212                     Temp_wall_zone2{i}(number_of_gridpoints(i),j+1) = Temp_wall_zone2{i}(number_of_gridpoints(i)
213                 end
214                 % Computation of the temperature of the struture of the tank(s)
215                 for k=2:number_of_gridpoints(i)-1
216                     if (k>=2)&&(k<=int_pt_liner_laminate(i)-1)
```

```
217                         Temp_wall_zone1{i}(k,j+1) = Temp_wall_zone1{i}(k,j)+CFL_liner(i)*(Temp_wall_
218                         Temp_wall_zone2{i}(k,j+1) = Temp_wall_zone2{i}(k,j)+CFL_liner(i)*(Temp_wall_
219                     elseif (k>=int_pt_liner_laminate(i)+1)&&(k<=number_of_gridpoints(i)-1)
220                         Temp_wall_zone1{i}(k,j+1) = Temp_wall_zone1{i}(k,j)+CFL_laminate(i)*(Temp_wa
221                         Temp_wall_zone2{i}(k,j+1) = Temp_wall_zone2{i}(k,j)+CFL_laminate(i)*(Temp_wa
222                     else
223                         Temp_wall_zone1{i}(k,j+1) = (cond_laminate(i)*(Temp_wall_zone1{i}(k+1,j)+CFL
224                         Temp_wall_zone2{i}(k,j+1) = (cond_laminate(i)*(Temp_wall_zone2{i}(k+1,j)+CFL
225                     end
226                 end
227             end
228 
229         end
230 
231     end
232 end
```

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