Novel Approaches to Fast Filling of Hydrogen Cylinders

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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, Dr. Edward Richardson, for his time, dedication, patience, and support throughout this project.

Furthermore, I would like to thank Vishagen Ramasamy for his initial work upon which this paper builds.

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

Abstract

This is the abstract.

Contents

Acronyms

CFD Computational Fluid Dynamics

Todo list

1 Introduction

{sec:introduction}

1.1 Purpose of the investigation

Hydrogen is a very promising alternative fuel for the future, mainly due to the absence of greenhouse emissions when burning it. In this regard, it is superior to current petroleum-, and more generally, carbon-based fueling systems. However, air pollution is a negative externality associated with carbon-based fuels, as it is a cost to a third party (in this case, society as a whole) that is not accounted for in the price of the good. By definition, the negative consequences of polluting the air are not accounted for in the price of carbon vehicles, and therefore will have little influence on a consumer's choice. Thus, if hydrogen is to succeed as an alternative to carbon fuels, it is essential that its use be as - if not more - convenient than traditional fuel.

Reword

One of the main aspects 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 (358 °K 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 in order to analyse novel methods of improving fill times.

1.2 Outline of the investigation

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, and phase change materials. 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.

Update with actual options considered at end of project

2 Background

kground}

2.1 Vehicles and objectives

We must firstly consider what real-world relevance of this project is. As explained in Section 1, the hydrogen cylinders being considered are for road vehicles. Although still an emerging technology, the basic functioning of a hydrogen fueled cylinders is relatively well established. They store compressed hydrogen in fuel tanks at high pressures, 35 and 70 MPa are the two current standards for pressure. Cite This hydrogen is then used in the fuel cell and converted into electricity,, which can be used directly by the electric motor or stored on onboard batteries. It therefore follows that the objectives of the hydrogen storage system are several:

- High fuel capacity
- Low overall weight
- Low fill times

These have certain implications. Firstly, it is clear that several tradeoffs and compromises must be made. Increasing fuel capacity can be done by either using larger tanks, which leads to higher weight, or using higher pressures, which inevitably leads to higher temperatures. These higher temperatures are problematic due to material constraints as explained below in Section 2.1.1. Indeed, they lead to longer filling times as heat is allowed to dissipate through the tank walls. This leads to the desire to optimize filling patterns and develop other solutions to minimize temperature rise when filling to high pressures.

Fill

2.1.1 Material constraints

{sec:materialConstr

The main reason that a problem exists, and consequently this paper (and much other work) is being undertaken, is the material limitations that exist in hydrogen cylinders. Indeed, the cylinders that are used for high pressure scenarios such as the one we are presented with, are constructed with a composite material such as carbon fibre or glass/aramid fibre. In addition, they have a liner that is made out of metal, typically aluminum, in Type III cylinders, and out of a thermoplastic material for Type IV cylinders. Of concern is the composite material, as the polymer matrix cannot withstand high temperatures, and as such the material properties of the cylinder will begin to degrade. The specific temperature at which this occurs is usually around the glass transition temperature of the epoxy, where the thermosetting polymer changes from a hard ”glassy” state to a more compliant ”rubbery” state.

cite: http://www.epotek

2.2 Previous work

We must first establish a baseline of previous work that has been conducted in this field, and subsequently analyze the shortcomings that exist in order to direct the research.

2.2.1 Modeling Work

A large amount of research has been conducted using multidimensional analysis, especially using Computational Fluid Dynamics (CFD). Indeed, there is myriad papers describing different methods and setups, such as Dicken and Mérida's work, which uses the standard k-ε turbulence model and the Redlich-Kwong real gas equation of state for real gas properties [1]. Some of these models use more advanced property models, such as the model presented by Zhao et al., which employs REFPROP (see Section 2.5.3) in order to have more precise real gas properties [2].

2.2.2 Experimental work

:experimental_work}

Several papers describe experimental work that has been conducted regarding the fast-filling of hydrogen cylinders, in particular comparing the results to simulations. Dicken and Mérida's work indicates that the temperature inside the cylinder is rather uniform [3]. This claim is not, however supported by the work of Zheng et al nor that of Woodfield et al [4], wherein large discrepancies among gas temperatures in different regions of the cylinder are found.

Citation

2.2.3 Analysis

The simulation work that has been conducted can be, in broad terms, divided into complex CFD models and more simplified 0-dimensional models. It is important analyze the difference between these two systems. The main advantage of reduced dimension models is that they are much less computationally expensive. This, in turn, means it can be incorporated as part of a larger analysis, in which it must be run multiple times, such as optimization routines or probabilistic whole station models.

Reduced dimension models assume a constant gas temperature, which, as outlined in Section 2.2.2, is supported by some experimental work, but refuted by others. For this reason, more research should be conducted to validate the uniform gas temperature approximation.

2.3 Cylinder filling models

Several ways of modelling the cylinder can be considered when analysing their filling, with varying complexity and accuracy.

2.3.1 Zonal

A zonal model, also referred to as a 0-dimensional model, refers to models that consider the gas inside the cylinder as the control volume, with homogenous properties. This allows for simpler calculations and much lower computational time.

Fill

2.3.2 Multidimensional

:multidimensional}

More complex multidimensional models can be created, either 2D axisymmetric models or full 3D models. 2D models will not include the effects of gravity or buoyancy, but these can be considered negligible, and the computational expense of full 3D simulations is rarely justifiable as the gains in accuracy are very small.

fill

2.4 Heat transfer models

In order to successfully analyse the behaviour of the system as a whole we must consider several local heat transfer methods that occur at different places inside of the cylinder.

2.4.1 Impinging jet

The first behaviour that we will consider is that of an impinging jet of fluid onto a surface.

FIGURE 1: Impinging jet

{fig:inpinging_jet}

2.4.2 Pipe flow

A second behaviour that we will consider is that of pipe flow. This behaviour has been the focus of much research, as it is arguably the most common mode of heat transfer that occurs in fluid systems.

2.4.3 Turbulent Jets

Lastly, we must also consider turbulent jets, as there will be such a situation at the exit of the nozzle. [5]

2.5 Methodology

Several techniques and methods will be used throughout the analysis. These are described in this section.

2.5.1 Optimization

Fill Section once work on optimization starts.

2.5.2 Non-dimensioning

One of the fundamental principals used throughout this paper, and indeed, throughout engineering, is that of non-dimensioning. By operating using non-dimensional parameters such as the Reynolds number $Re = \frac{\rho u L}{\nu}$ or the Prandtl number $Pr = \frac{c_p \mu}{k}$ solving problems involving differential equations becomes simplified. Also, the analysis becomes much more general, and can be scaled.

2.5.3 Numerical methods

{sec:num

Integrating ODEs An central part of solving unsteady heat transfer problems involves integrating ODEs, as will be seen in Section 3. One of the simplest methods available, both conceptually and in terms of ease of implementing in code, is forward Euler time integration. It can be informally described as follows: given a function that can be defined by:

$$y'(t) = f(t, y(t)), \quad y(t_0) = y_0 \tag{2.1}$$

we can compute the approximate shape of the function given the initial point and finding the slope of the curve for small intervals. Indeed, from the initial point, we can find the tangent of the curve at that point, and take a small step along that tangent until arriving at the next point, where the procedure can be repeated. Denoting the step size h, we can express forward Euler time integration as:

$$y_{n+1} = y_n + hf(t_n, y_n) \tag{2.2}$$

ec:property_models}

Property models As the gases that are being treated in this report are at very high pressures, ideal gas approximations are inaccurate, and thus real gas properties must be employed. To this end, property models must be used, which can determine any gas property from two other independent properties.

The property model that will be employed throughout this analysis is REFPROP, a tool developed by the National Institute of Standards and Technology [6]. It uses values of critical and triple points together with equations for the thermodynamic and transport properties to calculate the state points of fluids.

3 Formulation

{sec:formulation}

3.1 Heat transfer across cylinder

The main mode of heat transfer that occurs in the cylinder and that will be used throughout this report is heat conduction through the wall of the cylinder. This is modeled using:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{3.1}$$

where a is the thermal diffusivity, which is defined by :

$$\alpha = \frac{k}{\rho c} \tag{3.2}$$

where k is the material's thermal conductivity, ρ is the density of the material, and c is the specific heat capacity of the material. This differential equation will be solved using forward Euler time integration as described in Section 2.5.3.

3.2 Gas flow into cylinder

The nozzle and corresponding gas flow will be modeled using isentropic relations, and then a discharge coefficient relationship will be used to find the approximate real values. Indeed, the isentropic Reynold's number is first calculated as follows:

$$\mathrm{Re}_{\mathrm{ideal}} = \frac{\rho_{\mathrm{exit}}\, d_{\mathrm{inlet}}\, u_{\mathrm{exit}}}{\mu_{\mathrm{exit}}} \tag{3.3}$$

where ρ_{exit}, d_{inlet}, u_{exit}, and μ_{exit} are determined using real gas models as described in Section 2.5.3. In order to find the real mass flow an empirical discharge coefficient is employed:

$$\mathrm{CD} = \frac{\dot{m}_{\mathrm{in}}}{\dot{m}_{\mathrm{ideal}}} = A + B\,\mathrm{Re}_{\mathrm{ideal}} \tag{3.4}$$

A discharge coefficient must be used to account for the formation of a boundary layer inside the inlet tube. The empirical model that was used was obtained from , and uses the following values:

Citation

$$A = 0.938, \quad B = -2.71 \tag{3.5}$$

3.3 Hysteresis

The initial work this project builds upon uses the flow at the nozzle to determine the heat transfer at the wall of the cylinder. This assumes that the hydrogen flows instantaneously from the nozzle to the wall, when in reality there of course is a time delay, measured to be approximately 2 seconds for short cylinders. This assumption is acceptable for stable inflows, but for more complex filling patterns and also for improved accuracy it becomes necessary to incorporate hysteresis. Indeed, the heat transfer coefficient at the wall in fact can be said to depend on the nozzle flow seconds prior, or more generally, on the history of the nozzle flow. This can be modeled as follows:

define short and long cylinders at some point

$$\frac{d}{dt}\left(\mathrm{Nu}\right) = \frac{\mathrm{Nu}_{ss} - \mathrm{Nu}}{\tau} \tag{3.6}$$

3.4 Throttling

Throttling is introduced in order to more accurately represent real life conditions. When a maximum temperature is reached, the inflow of hydrogen must be stopped in order to protect the materials of the tank, as detailed in Section 2.1.1. A simple method of throttling, with the flow stopping at the designated maximum temperature, 85 °C, and the flow restarting at a chosen temperature, in this case 75 °C.

Play around with this perhaps?

3.5 Optimization

General stuff:
- Check tense and person
- Check for repetition
- Check for excessive verboseness

Appendices

A Filling Code

{app:filling_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
            % Constant inlet pressure profile
            P_inlet(i,j+1) = ConstPressKPa;
        else
            % Read inlet pressure profile from specified file
            P_inlet(i, j+1) = interp1(InletPressureData(:,1),InletPressureData(:,3), dt*j);
        end

        if blnUseStandardData == 1
            %Temp_inlet(i,j+1) = interp1(time_in, temp_in, dt*j);   % Temperature profile after the
            Temp_inlet(i, j+1) = ConstTempK;
        else
            % Read inlet temperature profile from specified file
            Temp_inlet(i, j+1) = interp1(InletTempData(:,1), InletTempData(:,3), dt*j);
        end

        h_inlet(i,j+1) = refpropm('H','T',Temp_inlet(i,j+1),'P',P_inlet(i,j+1),Fluid{i}, refpropdir)
        entropy_inlet(i,j+1) = refpropm('S','T',Temp_inlet(i,j+1),'P',P_inlet(i,j+1),Fluid{i}, refpr

        %% Determine which pressure to use at the exit of the delivery pipe which is dependent upon

        if l_d(i) > 3 && blnOneZone{i} == 0          % The length-to-diameter ratio of the tank(s) d
            Pressure_exit = P_gas_zone1{i}(j);   % The pressure at the exit of the delivery pipe is
        else
            Pressure_exit = P_gas(i,j);          % The pressure at the exit of the delivery pipe is
        end

        if (P_inlet(i,j+1) > Pressure_exit)  % condition for filling of tank(s)
            sound_exit(i,j+1) = refpropm('A','P',Pressure_exit,'S',entropy_inlet(i,j+1),Fluid{i}, re
            h_static_exit(i,j+1) = refpropm('H','P',Pressure_exit,'S',entropy_inlet(i,j+1),Fluid{i},
            visc_exit(i,j+1) = refpropm('V','P',Pressure_exit,'S',entropy_inlet(i,j+1),Fluid{i}, ref
            mach_exit(i,j+1) = sqrt(2*(h_inlet(i,j+1)-h_static_exit(i,j+1))/sound_exit(i,j+1)^2);

            %% If Mach number is greater than one, the exit pressure is greater than the pressure wi
            %  is incremetally increased and iterated in a while loop  until mach number is equal to

            Inlet_entropy = entropy_inlet(i,j+1);
            Inlet_stagnation_enthalpy = h_inlet(i,j+1);
            P_guess =  Pressure_exit;

            if mach_exit(i,j+1) > 1
                Pressure_exit = find_exit_pressure(Inlet_stagnation_enthalpy,Inlet_entropy,Fluid{i},
                sound_exit(i,j+1) = refpropm('A','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, refpr
                h_static_exit(i,j+1) = refpropm('H','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, re
```

```
                visc_exit(i,j+1) = refpropm('V','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, refpropdir);
                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
            end

            %% Calculation of the mass flow rate into the tank(s)

            rho_exit(i,j+1) = refpropm('D','P',Pressure_exit,'S',Inlet_entropy,Fluid{i}, refpropdir);
            vel_exit(i,j+1) = mach_exit(i,j+1)*sound_exit(i,j+1);                                    % Calcul
            Re_exit_isentropic(i,j+1) = rho_exit(i,j+1) *d_inlet*vel_exit(i,j+1)/visc_exit(i,j+1);     % Calcul
            cd(i,j+1) =  I + J/(Re_exit_isentropic(i,j+1)^(0.25));                                   % Calcul
            mfr(i,j+1) = cd(i,j+1)*rho_exit(i,j+1)*vel_exit(i,j+1)*A_inlet;                          % Calcul
            Re_entrance_actual(i,j+1)= 4*mfr(i,j+1)/(pi*d_inlet*visc_exit(i,j+1));                   % Calcul
            dM_inlet = mfr(i,j+1)*dt;                                                                % Amount
        end

        %% Heat transfer calculations & caluclations of the thermodynamic properties of the gas in the tank(s) w
        if l_d(i) <= 3 | blnOneZone{i} == 1

            Nus(i,j+1) =   a_1*Re_entrance_actual(i,j+1)^(b_1);                    % Nusselt number and Reynolds
            k_gas(i,j+1) = refpropm('L','T',Temp_gas(i,j),'P',P_gas(i,j),Fluid{i}, refpropdir);  % Thermal condu
            heat_coef_forced(i,j+1) = Nus(i,j+1)*k_gas(i,j+1)/d_tank(i);          % Calculation of the heat tran

            if Inner_wall_boundary(i) == 1
                Qsurf(i,j+1) = -dt*surf_area(i)*heat_coef_forced(i,j+1)*(Temp_gas(i,j)-Inner_temp_wall_isotherma
            else
                Qsurf(i,j+1) = -dt*surf_area(i)*heat_coef_forced(i,j+1)*(Temp_gas(i,j)-Temp_wall{i}(1,j));
                Temp_wall{i}(1,j+1) = Temp_wall{i}(1,j)+ CFL_liner(i)*(Temp_wall{i}(2,j)- Temp_wall{i}(1,j) - Qs

                if Outer_wall_boundary(i)==1
                    Temp_wall{i}(number_of_gridpoints(i),j+1) = Outer_temp_wall_isothermal(i);
                else
                    Temp_wall{i}(number_of_gridpoints(i),j+1) = Temp_wall{i}(number_of_gridpoints(i),j)+2*CFL_la
                end
                % Computation of the temperature of the struture of the tank(s)
                for k=2:number_of_gridpoints(i)-1
                    if (k>=2)&&(k<=int_pt_liner_laminate(i)-1)
                        Temp_wall{i}(k,j+1) = Temp_wall{i}(k,j)+CFL_liner(i)*(Temp_wall{i}(k+1,j)-2*Temp_wall{i}
                    elseif (k>=int_pt_liner_laminate(i)+1)&&(k<=number_of_gridpoints(i)-1)
                        Temp_wall{i}(k,j+1) = Temp_wall{i}(k,j)+CFL_laminate(i)*(Temp_wall{i}(k+1,j)-2*Temp_wall
                    else
                        Temp_wall{i}(k,j+1) = (cond_laminate(i)*(Temp_wall{i}(k+1,j)+CFL_laminate(i)*(Temp_wall-
                    end
                end
            end
            m_gas(i,j+1) = m_gas(i,j)+ dM_inlet;                                                 % Mass of gas in
            Ugas(i,j+1)=Ugas(i,j)+Qsurf(i,j+1)+h_inlet(i,j+1)*dM_inlet;                          % Internal energy
            u_gas(i,j+1)= Ugas(i,j+1)/m_gas(i,j+1);                                              % Specific energy
            rho_gas(i,j+1)=m_gas(i,j+1)/vol_tank(i);                                             % Density of the
            P_gas(i,j+1) = refpropm('P','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir);        %
            Temp_gas(i,j+1) = refpropm('T','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir);     %

        else
            Re_compression(i,j+1) = Re_entrance_actual(i,j+1)*(d_inlet/d_tank(i));               % Reynolds number

            Nus_zone1{i}(j+1) =  a_1*Re_entrance_actual(i,j+1)^(b_1);                           % Nusselt number
            Nus_zone2{i}(j+1) =  c_1*Re_compression(i,j+1)^(d_1);                               % Nusselt number

            k_gas_zone1{i}(j+1) =  refpropm('L','T',Temp_gas_zone1{i}(j),'P',P_gas_zone1{i}(j),Fluid{i}, refprop
            k_gas_zone2{i}(j+1) =  refpropm('L','T',Temp_gas_zone2{i}(j),'P',P_gas_zone2{i}(j),Fluid{i}, refprop

            heat_coef_forced_zone1{i}(j+1) =  Nus_zone1{i}(j+1)*k_gas_zone1{i}(j+1)/d_tank(i);            %
            heat_coef_forced_zone2{i}(j+1) =  Nus_zone2{i}(j+1)*k_gas_zone2{i}(j+1)/l_zone2_total(i);     %

            % Step 1. Equating the respecting values of zone 1 and zone 2 to
            % matrices with 'similar' names

```

```
        Vgas(1)=volume_zone1(i);
        Vgas(2)=volume_zone2(i);
        Mgas(1)=m_gas_zone1{i}(j);
        Mgas(2)=m_gas_zone2{i}(j);
        Ugas_twozone(1)=u_gas_zone1{i}(j)*Mgas(1);
        Ugas_twozone(2)=u_gas_zone2{i}(j)*Mgas(2);
        Asurf(1)=surface_area_zone1(i);
        Asurf(2)=surface_area_zone2(i);
        Tgas(1)=Temp_gas_zone1{i}(j);
        Tgas(2)=Temp_gas_zone2{i}(j);
        if Inner_wall_boundary(i) == 1
            Twall(1,1)=Inner_temp_wall_isothermal(i);
            Twall(2,1)=Inner_temp_wall_isothermal(i);
        else
            Twall(1,1)=Temp_wall_zone1{i}(1,j);
            Twall(2,1)=Temp_wall_zone2{i}(1,j);
        end
        % Step 2: apply the change of internal energy due to heat transfer and mass
        % input through nozzle:

        dM_inlet = mfr(i,j+1)*dt;

        Qsurf(1)=- dt*Asurf(1)*(heat_coef_forced_zone1{i}(j+1))*(Tgas(1)-Twall(1,1));
        Qsurf(2)=- dt*Asurf(2)*(heat_coef_forced_zone2{i}(j+1))*(Tgas(2)-Twall(2,1));

        Ugas_twozone(1)=Ugas_twozone(1)+Qsurf(1)+h_inlet(i,j+1)*dM_inlet;
        Ugas_twozone(2)=Ugas_twozone(2)+Qsurf(2);

        Mgas(1)=Mgas(1)+dM_inlet;
        Mgas(2)=Mgas(2);

        for m=1:2
            hgas(m)=refpropm('H','D',Mgas(m)/Vgas(m),'U',Ugas_twozone(m)/Mgas(m),Fluid{i}, refpr
        end


        % Step 2: Find the amount of mass that needs to be transferred from zone 1
        % to zone 2 to equalise their pressure
        % (we assume forward Euler integration, therefore we use the specific
        % enthalpies h from the start of the timestep. We provide enthalpies for
        % both zones in case the flow gets reversed).

        dM_guess = dM_inlet*(volume_zone2(i)/(volume_zone1(i)+volume_zone2(i))) ;
        dM_12 = find_dM_12(hgas,Vgas,Mgas,Ugas_twozone,Fluid{i},dM_guess, refpropdir);

        % Step 3: Apply this change to the mass and update all properties:

        m_gas_zone1{i}(j+1)=Mgas(1)-dM_12;
        m_gas_zone2{i}(j+1)=Mgas(2)+dM_12;

        u_gas_zone1{i}(j+1)=(Ugas_twozone(1)-max(0,dM_12)*hgas(1)-min(0,dM_12)*hgas(2))/m_gas_zo
        u_gas_zone2{i}(j+1)=(Ugas_twozone(2)+max(0,dM_12)*hgas(1)+min(0,dM_12)*hgas(2))/m_gas_zo

        rho_gas_zone1{i}(j+1)=m_gas_zone1{i}(j+1)/volume_zone1(i);
        rho_gas_zone2{i}(j+1)=m_gas_zone2{i}(j+1)/volume_zone2(i);

        Temp_gas_zone1{i}(j+1)=refpropm('T','D',rho_gas_zone1{i}(j+1),'U', u_gas_zone1{i}(j+1),F
        Temp_gas_zone2{i}(j+1)=refpropm('T','D',rho_gas_zone2{i}(j+1),'U', u_gas_zone2{i}(j+1),F

        P_gas_zone1{i}(j+1)=refpropm('P','D',rho_gas_zone1{i}(j+1),'U', u_gas_zone1{i}(j+1),Flui
        P_gas_zone2{i}(j+1)=refpropm('P','D',rho_gas_zone2{i}(j+1),'U', u_gas_zone2{i}(j+1),Flui

        m_gas(i,j+1) = m_gas_zone1{i}(j+1) + m_gas_zone2{i}(j+1);
        rho_gas(i,j+1) = m_gas(i,j+1)/vol_tank(i);
        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{
        Ugas(i,j+1) = u_gas(i,j+1)*m_gas(i,j+1);
```

```
            Temp_gas(i,j+1)  = refpropm('T','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir);
            P_gas(i,j+1)  = refpropm('P','D',rho_gas(i,j+1),'U',u_gas(i,j+1),Fluid{i}, refpropdir);

            if Inner_wall_boundary(i) == 1
                Qsurf_zone1{i}(j+1) = -dt*surface_area_zone1(i)* heat_coef_forced_zone1{i}(j+1)*(Temp_gas_zone1-
                Qsurf_zone2{i}(j+1) = -dt*surface_area_zone2(i)* heat_coef_forced_zone2{i}(j+1)*(Temp_gas_zone2-
            else
                Qsurf_zone1{i}(j+1) = -dt*surface_area_zone1(i)* heat_coef_forced_zone1{i}(j+1)*(Temp_gas_zone1-
                Qsurf_zone2{i}(j+1) = -dt*surface_area_zone2(i)* heat_coef_forced_zone2{i}(j+1)*(Temp_gas_zone2-

                Temp_wall_zone1{i}(1,j+1) = Temp_wall_zone1{i}(1,j)+ CFL_liner(i)*(Temp_wall_zone1{i}(2,j)- Temp
                Temp_wall_zone2{i}(1,j+1) = Temp_wall_zone2{i}(1,j)+ CFL_liner(i)*(Temp_wall_zone2{i}(2,j)- Temp

                if Outer_wall_boundary(i)==1
                    Temp_wall_zone1{i}(number_of_gridpoints(i),j+1) = Outer_temp_wall_isothermal(i);
                    Temp_wall_zone2{i}(number_of_gridpoints(i),j+1) = Outer_temp_wall_isothermal(i);
                else
                    Temp_wall_zone1{i}(number_of_gridpoints(i),j+1) = Temp_wall_zone1{i}(number_of_gridpoints(i)
                    Temp_wall_zone2{i}(number_of_gridpoints(i),j+1) = Temp_wall_zone2{i}(number_of_gridpoints(i)
                end
                % Computation of the temperature of the struture of the tank(s)
                for k=2:number_of_gridpoints(i)-1
                    if (k>=2)&&(k<=int_pt_liner_laminate(i)-1)
                        Temp_wall_zone1{i}(k,j+1) = Temp_wall_zone1{i}(k,j)+CFL_liner(i)*(Temp_wall_zone1{i}(k+1
                        Temp_wall_zone2{i}(k,j+1) = Temp_wall_zone2{i}(k,j)+CFL_liner(i)*(Temp_wall_zone2{i}(k+1
                    elseif (k>=int_pt_liner_laminate(i)+1)&&(k<=number_of_gridpoints(i)-1)
                        Temp_wall_zone1{i}(k,j+1) = Temp_wall_zone1{i}(k,j)+CFL_laminate(i)*(Temp_wall_zone1{i}(
                        Temp_wall_zone2{i}(k,j+1) = Temp_wall_zone2{i}(k,j)+CFL_laminate(i)*(Temp_wall_zone2{i}(
                    else
                        Temp_wall_zone1{i}(k,j+1) = (cond_laminate(i)*(Temp_wall_zone1{i}(k+1,j)+CFL_laminate(i)
                        Temp_wall_zone2{i}(k,j+1) = (cond_laminate(i)*(Temp_wall_zone2{i}(k+1,j)+CFL_laminate(i)
                    end
                end
            end

        end

    end
end
```

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