ANALYSIS OF HEAT STORAGE WITH A THERMOCLINE TANK FOR CONCENTRATED SOLAR PLANTS

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ANNEX A: Repeated cycles with charge and discharge processes

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eps = 0.22; % porosity of the solid filler rock
rhol = 1733; % density of the molten salt
cpl = 1520; % specific heat of the molten salt
kl = 0.57; % thermal conductivity of the molten salt
mul = 0.0021; % dynamic viscosity of the molten salt
mdots = 948; % mass flow rate of the salt
%
rhos = 2500; % density of the filler rock
cps = 830; % specific heat of the filler solid rock;
ks = 5; % thermal conductivity of the filler rock
dr = 0.015; % effective diameter of the rock granules
%
H = 18; % tank height
D = 38.5; % diameter of the tank
V = pi*D*D*H/4;
%
N = 500;
%
U = 1*mdots/(rhol*eps*pi*(D/2)^2);
td = 7.5;
tc = 7.5;
piD = td*3600*U/H; % discharge time period
piC = tc*3600*U/H; %charge time period

%FULLY CHARGED TANK
ul0 = ones(N,1);
us0 = ones(N,1);

%CYCLE 1
figure(1)
[ul1] =
Ldischarge(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul1(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(2)
[ul2] =
Lcharge(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul2(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 2
figure(3)
[ul3] =
Ldischarge2(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul3(1:N,16);
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ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(4)
[ul4] =
Lcharge2(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul4(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 3
figure(5)
[ul5] =
Ldischarge3(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul5(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(6)
[ul6] =
Lcharge3(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul6(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 4
figure(7)
[ul7] =
Ldischarge4(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul7(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(8)
[ul8] =
Lcharge4(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul8(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 5
figure(9)
[ul9] =
Ldischarge5(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul9(1:N,16);

ul0 = ul0i(end:-1:1);
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us0 = ul0i(end:-1:1);

figure(10)
[ul10] =
Lcharge5(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul10(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 6
figure(11)
[ul11] =
Ldischarge6(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul11(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(12)
[ul12] =
Lcharge6(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul12(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 7
figure(13)
[ul13] =
Ldischarge7(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul13(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(14)
[ul14] =
Lcharge7(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul14(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 8
figure(15)
[ul15] =
Ldischarge8(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul15(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);
```

```
figure(16)
[ul16] =
Lcharge8(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul16(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 9
figure(17)
[ul17] =
Ldischarge9(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul17(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(18)
[ul18] =
Lcharge9(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);

ul0i = ul18(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

%CYCLE 10
figure(19)
[ul19, Energia, int, taur, Hcr] =
Ldischarge10(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);

ul0i = ul19(1:N,16);

ul0 = ul0i(end:-1:1);
us0 = ul0i(end:-1:1);

figure(20)
[ul20] =
Lcharge10(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piC);



EdischargedIdeal = mdots*cpl*(384-291)*(td*3600)

eff = Energia/EdischargedIdeal

eff2 = int/piD
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ANNEX B: Discharge process function

```
function [ul, Edischarged, Integral, taur, Hcr] =
discharge10(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,td)

alpha = kl/rhol*cpl;                    % thermal diffusivity of the salt
%
beta = (ks-kl)/(ks+2*kl);
phi = 1-eps;
keff = 0.01*kl*(1+2*beta*phi+(2*beta^3-
0.1*beta)*phi^2+phi^3*0.05*exp(4.5*beta))/...
    (1-beta*phi);                       % eq. 6 of Flueckiger et al 2014
alphaeff = keff/rhol/cpl;

%
R = D/2;
U = 1*mdots/(rhol*eps*pi*R^2);                     % velocity fo the salt
G = mdots/(eps*pi*R^2);
r = dr/2;
rchar  = eps*dr/(4*(1-eps));                           % Lew et al eq. 12
Ref = 4*G*rchar/mul;                                   % Lew et al eq. 10
Pr = cpl*mul/kl;                             % Prandtl number of the salt
Pe = H*U/alpha;                                           % peclet number
Pe_eff = H*U/alphaeff;

hii = 1*0.191*mdots*cpl*Ref^(-0.278)*Pr^(-2/3)/(eps*pi*D*D/4) % eq.9 of Lew
Bi = hii*(dr/2)/ks;                                     % Biot correction
hi = hii/(1+Bi/5);

ms = (1-eps)*rhos*cps;                 % thermal mass of the rock [J/m3·K]
ml = eps*rhol*cpl;              % thermal mass of the molten salt [J/m3·K]
%
Sr = 3*pi*R^2*(1-eps)/r;
taur = 1*(U/H)*(rhol*cpl*eps*R^2*pi/(hi*Sr));
Hcr = 1*rhol*cpl*eps/(rhos*cps*(1-eps));

%POINTS
dx = 1/N;                                                % interval size

%TIME
dt = 1e-3;
tSHOW = td/15;                          % times that outputs are stored
MSHOW = floor(tSHOW/dt);            % number of time steps between outputs
KSHOW = floor(td/tSHOW)+1;                   % number of output snapshots



ul00 = 0;                                  % inlet condition of the salt
us00 = 0;                           % inlet condition of the filler rock
BC0 = 1;                  % inlet boundary condition type (1- specified temp)

%SYSTEM MATRIX
B = (diag(ones(N-1,1),1)+diag(-ones(N-1,1),-1))/(2*dx);
C = -(1*1/Pe_eff/(dx*dx))*(-2*eye(N)+diag(ones(N-1,1),1)+diag(ones(N-1,1),-
1));
A = B+C+eye(N)*(1/dt+(1/taur));
%
```

```
A(N,N) = -1/dx*(3/2);          % convection boundary condition at the exit
A(N,N-1) = 1/dx*(2);                                       % conv. b.c. exit
A(N,N-2) = -1/dx*(1/2);                                    % conv. b.c. exit
%
A1 = inv(A);                                  % inversion of system matrix
%
uul = ul0;                        % previous solution for salt initialized
uus = us0;                      % previous solution for filler initialized
uus0 = us00;                                       % filler inlet condition
%
K = floor(td/dt)+1;                                  % number of time-steps
mshow = 1;                   % initialize the variable for stored outputs
ul = ul00*ones(N+1,KSHOW);                   % initialize stored outputs
us = ones(N+1,KSHOW);                        % initialize stored outputs
ul(2:N+1,1) = ul0;                             % store initial condition
us(2:N+1,1) = us0;                             % store initial condition
%
bc = zeros(N,1);                                             % empty array!
%
thot = 384;
tcold = 291;
tl = zeros(K,1);
tout = zeros(K,1);
%
for m = 1:K
    usk = (uus/dt+uul*Hcr/taur)/(1/dt+Hcr/taur);
    usk(1,1) = (uus0/dt+ul00*Hcr/taur)/(1/dt+Hcr/taur);
    bc(1) = ul00*(1/(2*dx));                  % inlet boundary condition
    f = uul/dt+usk/taur+bc;
    f(N) = 0;
    ulk = A1*f;
    uul = ulk;
    uus = usk;
    tout(m,1) = ulk(N,1);
    if rem(m,MSHOW) == 0
        disp(m*dt);
        mshow = mshow +1;
        ul(2:N+1,mshow) = ulk;
        us(2:N+1,mshow) = usk;
        ul(1,mshow) = ul00;
    end
end

x = [0:dx:1];
plot(x,ul);
xlabel('z*')
ylabel('Fluid temperature')
axis([0 1 0 1]);
grid on;

tcc = ones(K,1)*tcold;
tl = (thot-tcold)*tout+tcc;
interv = tl-tcc;
Edischarged = sum(interv*mdots*cpl*(7.5*3600/(K-1)))
Integral = sum(tout*dt);

figure(21)
t = [0: 4/(K-1) :4];
plot(t,tout);
axis([0 4 0 1]);
```

ANNEX C: Effect of the ratio H/D on the energy storage efficiency

```
y = H/D;
x2 = zeros(5,1);
x2(1,1) = y;
effv = zeros(5,1);
effv(1,1) = eff2;

for x = 2:5
    y = y+1;
    D = ((4*V)/(pi*y))^(1/3);
    H = y*D;
    x2(x,1) = y;
    [ul19, Energia, int, taur, Hcr] =
Ldischarge10(eps,rhol,cpl,kl,mul,mdots,rhos,cps,ks,dr,H,D,N,ul0,us0,piD);
    effv(x,1) = int/piD;
end

figure(22)
plot(x2,effv)
axis([0 5 0.95 1])

hold on
scatter(x2,effv,15,'r','fill');

xlabel('H/D')
ylabel('Energy storage efficiency')
grid on
title(['Effect of the ratio Height/Diameter on the storage efficiency']);
```