

Appendix A: Scaling – Geometry and Flowrates

The following calculations discuss the procedures used to obtain blade scaling factors and coolant flowrates for low-speed experimental tests and computations. In particular scaling along the tip (Blair, 2002) is highlighted as well as coolant flowrates for the tip (Blair, 2002) and platform models. Scaling of platform models is omitted as the same methods are followed to achieve platform scales with the numbers varying slightly.

A.1. Scaling

The primary goal of the scaling exercise is to match the external Re number along the tip

$$Re_e = \frac{\rho_e U_e C_e}{\mu_e} = Re_t = \frac{\rho_t U_t C_t}{\mu_t}$$

reorganization of terms yields the following equation

$$\frac{\rho_t U_t}{\rho_e U_e} = \frac{C_e \mu_t}{C_t \mu_e} = \frac{1}{S} \frac{\mu_t}{\mu_e} \quad (A-1)$$

where S is the scaling factor

The tip engine Reynolds number is given as follows:

$$Re_e = \frac{\rho_e U_e C_e}{\mu_e} = \frac{(0.21)(573)(0.075)}{(0.43E-4)} = 2.09E5$$

Experimental tests conditions are limited in the maximum speed of the facility as well as the properties of air fixed at near atmospheric conditions:

U_t is limited to 40.7 ft/s as well as ρ_t and μ_t

$$Re_t = \frac{\rho_t U_t C_t}{\mu_t} = \frac{(6.071)(40.7)C_t}{1.27E-5} = 226250 C_t$$

$$Re_e = Re_t$$

Solving for C_t yields a tip scale factor of 12

Also, one must allow for a minimum of a least two pitches within the facility which the 12X scaling factor allows.

The same procedure was used to scale the platform models except it was necessary to match only half of the engine mainstream Reynolds number thereby creating room for three pitches and an 11X scale.

A2. Tip Flowrates

The flow area for the equivalent engine flow (EEF) can be assumed as (1.55'')(span)

The “equivalent” engine should have the same span/pitch ratio as the test rig

$$\frac{\text{span}}{\text{pitch}} = \frac{1.55'}{1.84'} = 0.8564$$

This fixes the EEF span at 1.81''

EEF flow:

$$\dot{m}_e = \frac{(1.81)(1.55)}{144} \times (0.21)(573) = 2.344 \text{ lbm/s}$$

Returning to the earlier scaling equation A1

$$\frac{\rho_t U_t}{\rho_e U_e} = \frac{1}{S} \frac{\mu_t}{\mu_e}$$

$$\frac{\rho_t U_t A_t}{\rho_e U_e A_e} = \frac{\dot{m}_t}{\dot{m}_e} = \frac{1}{S} \frac{\mu_t A_t}{\mu_e A_e} = S \frac{\mu_t}{\mu_e} \quad (\text{A-2})$$

To relate % test rig to % engine (WAE) we combine equations to yield

$$\frac{\% \text{ Test}}{\% \text{ WAE}} = \left(S \frac{\mu_{ct}}{\mu_{ce}} \right) \left(\frac{1}{S} \frac{\mu_t}{\mu_e} \right) = \frac{\mu_{ct} \mu_e}{\mu_{ce} \mu_t}$$

The above to ratios are as follows:

$$\left(\frac{\mu_{ce}}{\mu_{ct}} \right) = 1.9 \text{ (coolant)}$$

$$\left(\frac{\mu_e}{\mu_t} \right) = 3.4 \text{ (mainstream)}$$

$$\frac{\% \text{ Test}}{\% \text{ WAE}} = \frac{3.4}{1.9} = 1.79$$

If the external Reynolds number is matched then the blowing ratio will not match

$$\frac{\rho_t U_t}{\rho_e U_e} = \frac{1}{S} \frac{\mu_t}{\mu_e} \quad (\text{external}) \qquad \frac{\rho_{ce} U_{ce}}{\rho_{ct} U_{ct}} = S \frac{\mu_{ce}}{\mu_{ct}} \quad (\text{coolant})$$

Combining the two equations above yields

$$\left(\frac{\rho_{ce} U_{ce}}{\rho_{ct} U_{ct}} \right) \left(\frac{\rho_t U_t}{\rho_e U_e} \right) = \left(S \frac{\mu_{ce}}{\mu_{ct}} \right) \left(\frac{1}{S} \frac{\mu_t}{\mu_e} \right)$$

$$M = \left(\frac{\rho_{ct} U_{ct}}{\rho_t U_t} \right) = \left(\frac{\rho_{ce} U_{ce}}{\rho_e U_e} \right) \frac{\mu_{ct}}{\mu_{ce}} \frac{\mu_e}{\mu_t}$$

The blowing ratio becomes

$$\frac{M_t}{M_e} = \frac{\mu_{ct}}{\mu_{ce}} \frac{\mu_e}{\mu_t} = 3.4 \frac{1}{1.9} = 1.79$$

If $Re_t = Re_e$ then the test M will be 1.79 times larger than the engine M .

To find % WAE for the EEF

$$\% \text{ WAE} = \frac{\dot{m}_t}{\dot{m}_e}$$

$$\dot{m}_e = 2.344 \text{ lbm/s} \quad (\text{previously calculated})$$

$$\dot{m}_c = 0.02349 \text{ lbm/s} \quad (\text{calculated from PW flow network code})$$

$$\% \text{ WAE} = \frac{0.02349}{2.344} = 1.002\%$$

Computation of a specified flow path (1936) yields a Reynolds number of $Re_{ce} = 23,500$

$$\dot{m}_c = \rho U A = \left(\frac{0.00055}{144} \right) (0.623) (618.6) = 0.001472 \text{ lbm/s}$$

(the above value is close to P783 value of 0.001449)

for EEf

$$\frac{\dot{m}_{c,1936}}{\dot{m}_{c,total}} = \left(\frac{0.001449}{0.023487} \right) = 0.006169$$

$$D_{ht} = S D_{he}$$

$$Re_{ce} = Re_{ct}$$

$$Re_{ce} = \frac{\rho_{ct} U_{ct} D_{ht}}{\mu_{ct}}$$

$$U_{ct} = \frac{(23500)(1.24E-5)}{(12) \left(\frac{.0212}{12} \right) (0.072)} = 194.5 \text{ ft/s}$$

$$\dot{m}_{ct,1936} = \rho U A = (0.092)(194.5) \left(\frac{0.00055(144)}{144} \right) = 0.0077 \text{ lbm/s} \quad (\text{for one flow path})$$

$$\dot{m}_{ct,1936} = \rho U A = (0.0077) \left(\frac{\dot{m}_{c,total}}{\dot{m}_{c,1936}} \right) = 0.1249 \text{ lbm/s}$$

(total coolant mass flow from flow network solver)

$$\dot{m}_t = 8.09 \text{ lbm/s} \quad (\text{flowrate through VT wind tunnel})$$

Final flows through the microcircuit

$$\%WAE = 1.002\% \Rightarrow 1.0\%$$

$$\%RIG = 1.54\% \Rightarrow 1.5\%$$

A3. Platform Flowrates

As discussed, the test section external/passage Reynolds number will be ½ the engine number. If we also match the internal channel Reynolds numbers to ½ the engine conditions, the ratio of blowing ratios becomes

$$\frac{M_t}{M_e} = 1.79 \quad (A-3)$$

as found by Mike Blair (2/26/02) and Brett Teller (2/21/03). This is valid for all cooling schemes (i.e. pressure side microcircuit, gutter, etc).

Using this relationship, a correlation can be made between the mass flow rate for the test section and the engine conditions. By expanding equation 3, the following relationship is found:

$$\frac{\rho_{ct} U_{ct} / \rho_t U_t}{\rho_{ce} U_{ce} / \rho_e U_e} = 1.79 \text{ (from Mike Blair's calculations 2/26/02)}$$

$$\frac{\rho_{ct} U_{ct}}{\rho_{ce} U_{ce}} = 1.79 \frac{\rho_t U_t}{\rho_e U_e}$$

$$\rho_e U_e = \left(0.21 \frac{\text{lbm}}{\text{ft}^3}\right) \left(970 \frac{\text{ft}}{\text{s}}\right) = 203.7 \frac{\text{lbm}}{\text{ft}^2 \text{s}} = 1.414 \frac{\text{lbm}}{\text{in}^2 \text{s}}$$

$$\rho_t U_t = \left(4.4 \times 10^{-5} \frac{\text{lbm}}{\text{in}^3}\right) \left(393.7 \frac{\text{in}}{\text{s}}\right) = 0.0173 \frac{\text{lbm}}{\text{in}^2 \text{s}}$$

$$\frac{\rho_{ct} U_{ct}}{\rho_{ce} U_{ce}} = 1.79 \frac{0.0173}{1.414} = 0.0219 \quad (\text{A-4})$$

Using the above relation (4), along with the general relationship of

$$\rho U = \frac{\dot{m}}{A}$$

allows the correlation between any given cooling scheme. If the mass flow rate and area are known for the engine, we can find the correct values for the VT test section, as shown in equation 5.

$$\rho_{ct} U_{ct} = 0.0219 \frac{\dot{m}_{ce}}{A_{ce}} \quad (\text{A-5})$$

Consider the pressure side microcircuit as an example:

At engine scale, $\dot{m} = 0.005098 \frac{\text{lbm}}{\text{s}}$ and $A = 0.0040 \text{ in}^2$, as taken from Brett Teller's results of the P783 solver. Now follow through the calculations:

$$\rho_{ce} U_{ce} = \frac{\dot{m}_{ce}}{A_{ce}} = \frac{0.005098 \frac{\text{lbm}}{\text{s}}}{0.004 \text{ in}^2} = 1.2745 \frac{\text{lbm}}{\text{in}^2 \text{s}}$$

$$\rho_{ct} U_{ct} = 0.0219 \frac{\dot{m}_{ce}}{A_{ce}} = 0.0279 \frac{\text{lbm}}{\text{in}^2 \text{s}}$$

Given that the exit area, $A = 0.484 \text{ in}^2$ in the test section, we can determine the test section mass flow rate as

$$\dot{m} = \rho_{ct} U_{ct} A = \left(0.0279 \frac{\text{lbm}}{\text{in}^2 \text{s}}\right) (0.484 \text{ in}^2) = 0.0135 \frac{\text{lbm}}{\text{s}},$$

which is 0.27% of the passage flow rate. Also, the blowing ratios and momentum flux ratios can be found as

$$M_e = \frac{1.2745}{1.414} = 0.901$$

$$M_t = \frac{0.0279}{0.0173} = 1.613$$

Following this method, the values in Table 1 were found for all cooling schemes to be tested on the platform section. For the feather seal, front-rim geometry, and aft rim geometry, the Reynolds number is based on the width of the gap.

Table A.1. Summary of Flow Calculations

	ρU (lbm/in ² s)		Area (in ²)		Mass Flow %		Reynolds		M	
	Engine	Test	Engine	Test	Engine	Test	Engine	Test	Engine	Test
PS M/C	1.275	0.028	0.004	0.484	0.14	0.27	20,970	10,485	0.90	1.614
SS M/C	0.965	0.021	0.004	0.508	0.11	0.21	15,960	7,980	0.68	1.2216
feather seal	2.180	0.048	0.003	0.391	0.18	0.37	142	71	1.54	2.7597
Front Rim	0.311	0.007	0.105	12.678	0.87	1.71	1,075	537	0.22	0.3937
Aft Rim	0.33	0.007	0.106	12.88	0.96	1.85	1,140	570	0.23	0.4177

Appendix B: Computer Programs

Included in this section are various computer programs that were used to create plots of non-dimensional temperature and pressure in MATLAB 6.xx. These programs which include BOAS.m, Tip.m and DPC.m were used exclusively for the tip analysis. BOAS.m plots temperature and pressure along the shroud based on inputs from the user. Tip.m plots pressure along the tip while DPC.m plots temperature. All three programs were compiled by Christophel [2003] to import three columns of data with the first two being position and the third being the contour variable.

Also included in this section is a sample Fluent 6.xx journal file used to create a data analysis plane. These journal files were utilized to speed the process of creating and analyzing data. A MATLAB program written by Knost [2003], LongitudinalAvgNew.m, computes pitchwise averaged data as was discussed in Chapter 4.

B1. BOAS.m – Contour plot of temperature and pressure along BOAS

```
function boas(filename,ptswitch,dpswitch,fileout)
%Jesse Christophel | 12-10-02 | Pratt & Whitney
%-----
%This file takes computational data for a blade
%BOAS only in 3-column format [X Y Z] where Z is
%dependent variable.
%-----
%function boas(filename,ptswitch,dpswitch,fileout)
%Call the function with the file name you want,
%followed by two switch commands
%ptswitch:    1 for Pressure
%             0 for Temperature
%dpswitch:    1 for TRUE
%             0 for FALSE
%-----
%Set graph spacing
xlength = 500;
ylength = 1000;
%Set graph x,y limits
xlim = [-.05,.45];
ylim = [-.1,.65];
%Load an (n x 3) matrix where column 1 is X, column 2 is Y, column 3 is Z
mat = load(filename);
%Load blade data
bp = load('PressureCoords.txt');
bs = load('SuctionCoords.txt');
bp(:,2) = bp(:,2) + 0.3797;
bs(:,2) = bs(:,2) + 0.3797;
%Begin matrix manipulation
Mins = min(mat);
Maxs = max(mat);
x = linspace(Mins(1),Maxs(1),xlength);
y = linspace(Mins(2),Maxs(2),ylength);
%For pressure files-----
if ptswitch==1
```



```

[X,Y,P] = griddata(mat(:,1),mat(:,2),mat(:,3),x,y');
Pt = 198;
Pd = .5*1.225*12.4*12.4;
Ps = Pt - Pd;
CP = (P - Ps)./Pd;
cpmid = find(CP<=1.1 & CP>=0);
CP(cpmid) = -.00001;
cphigh = find(CP>=0);
CP(cphigh) = NaN;
CP_max = max(max(CP))
CP_max = abs(fix(CP_max));
CP_min = min(min(CP))
CP_min = abs(fix(CP_min));
ehohl = CP_min + CP_max;
yLine = -1.1644*x + 0.2297;
for i=1:length(x)
    %     Collnd = x(i);
    %     YInd = find(Y(:,Collnd) < yLine(i));
    %     if length(YInd)>0
    %         CP(YInd,Collnd) = NaN;
    %     end
    YInd = find(y < yLine(i));
    if length(YInd) > 0
        CP(YInd,i) = NaN;
    end
end
%Make plots
figure(1);
[c,ch,cf] = contourf(X,Y,CP,ehohl);
set(ch,'LineStyle', 'none');
hold on;
%clabel(cs);
C0 = [127 0 7]/255;
C1 = [255 0 0]/255;
C2 = [255 97 0]/255;
C3 = [255 150 0]/255;
C4 = [255 182 0]/255;
C5 = [255 220 0]/255;
C6 = [255 255 0]/255;
C7 = [214 255 0]/255;
C8 = [173 255 0]/255;
C9 = [123 255 0]/255;
C10 = [0 255 123]/255;
C11 = [0 255 222]/255;
C12 = [0 223 255]/255;
C13 = [0 166 255]/255;
C14 = [0 0 255]/255;
C15 = [0 20 96]/255;
m = [C15; C14; C13; C12; C11; C10; C9; C8; C7; C6; C5; C4; C3; C2; C1; C0];
colormap(m)
axi = [-16 0];
caxis(axi);
axis tight; axis equal;
colorbar;
plot(bp(:,1),bp(:,2),'k');

```

```

    plot(bs(:,1),bs(:,2),'k');
    axis([xlim,ylim]);
end
%For temperature files-----
if ptswitch==0
    [X,Y,N] = griddata(mat(:,1),mat(:,2),mat(:,3),x,y');
    yLine = -1.1644*x + 0.2297;
    for i=1:length(x)
        YInd = find(y < yLine(i));
        if length(YInd) > 0
            N(YInd,i) = NaN;
        end
    end
    C0 = [255 0 0]/255;
    C1 = [255 43 0]/255;
    C2 = [255 85 0]/255;
    C3 = [255 128 0]/255;
    C4 = [255 170 0]/255;
    C5 = [255 212 0]/255;
    C6 = [255 255 0]/255;
    C7 = [191 255 0]/255;
    C8 = [128 255 0]/255;
    C9 = [64 255 0]/255;
    C10 = [0 255 0]/255;
    C11 = [0 255 64]/255;
    C12 = [0 255 128]/255;
    C13 = [0 255 191]/255;
    C14 = [0 255 255]/255;
    C15 = [0 204 255]/255;
    C16 = [0 153 255]/255;
    C17 = [0 102 255]/255;
    C18 = [0 51 255]/255;
    C19 = [0 0 255]/255;
    m = [C0; C1; C2; C3; C4; C5; C6; C7; C8; C9; C10; C11; C12; C13; C14; C15; C16; C17; C18; C19];
    [c,ch,cf] = contourf(X,Y,N,20); axis equal;
    hold on; plot(bp(:,1),bp(:,2),'k'); plot(bs(:,1),bs(:,2),'k');
    set(ch,'LineStyle','none');
    axi = [0 1];
    caxis(axi); axis tight; axis equal;
    colorbar;
    colormap(m)
    colorbar;
    axis equal;
    axis off;
    axis([xlim,ylim]);
end
if dpswitch==1
    dpx = [.0588,.0880,.0843,.0551];
    dpy = [.3949,.3910,.3632,.3671];
    plot(dpx(1:2),dpy(1:2),'k');
    plot(dpx(3:4),dpy(3:4),'k');
    LeftArc = load('LeftArc.txt');
    x = LeftArc(:,2);
    y = LeftArc(:,1);
    plot(x,y,'k');
    RightArc = load('RightArc.txt');

```

```

x = RightArc(:,2);
y = RightArc(:,1);
plot(x,y,'k');
x = .005*cos([0:10:360]*(pi/180));
y = .005*sin([0:10:360]*(pi/180));
xR = x + .09;
yR = y + .3765;
xL = x + .058;
yL = y + .3811;
plot(xR,yR,'k');
plot(xL,yL,'k');
axis([xlim,ylim]);
end
if nargin==4
    save(fileout,'dude','-ASCII','-DOUBLE','-TABS');
end

```

B2. Tip.m – Contour plot of pressure along tip

```

function tip(filename)
%JRC 9-4-02
%Pratt&Whitney
%Data Plotting Feat. Dan Knost
%
%Makes Cp contours for tip files
%
tic
%Set graph spacing
xlength = 500;
ylength = 1000;
%Set graph x,y limits
xlim = [-.05,.45];
ylim = [-.1,.65];
%Load an (n x 3) matrix where column 1 is X, column 2 is Y, column 3 is Cp
%mat = load('Z:\Pratt&Whitney\Temperature\new_adapt1_mdp_3mm_low.txt');
%mat = load('Z:\Pratt&Whitney\Temperature\new_adapt1_mdp_9mm_low.txt');
mat = load(filename);
%Load blade data
bp = load('PressureCoords.txt');
bs = load('SuctionCoords.txt');
bp(:,2) = bp(:,2) + 0.3797;
bs(:,2) = bs(:,2) + 0.3797;
%Begin matrix manipulation
Mins = min(mat);
Maxs = max(mat);
x = linspace(Mins(1),Maxs(1),xlength);
y = linspace(Mins(2),Maxs(2),ylength);
[X,Y,P] = griddata(mat(:,1),mat(:,2),mat(:,3),x,y);
Pt = 198;
Pd = .5*1.225*12.4*12.4;
Ps = Pt - Pd;
CP = (P - Ps)./Pd;
%Needed only for TIP files
bp_cut = bp(1:(end-10),:);

```

```

PS_pp = spline(bp_cut(:,1),bp_cut(:,2));
%Needed only for TIP files
BladeX = find(min(bp_cut(:,1)) <= x & x <= max(bp_cut(:,1)));
BladeX_Val = x(BladeX);
PS = ppval(PS_pp,BladeX_Val);
for i=1:length(BladeX)
    ErrInd = find(y < PS(i));
    if length(ErrInd) > 0;
        CP(ErrInd,BladeX(i)) = NaN;
    end
end
%Make plots
figure(1);
[c,ch,cf] = contourf(X,Y,CP,16);
set(ch,'LineStyle', 'none');
hold on;
%clabel(cs);
C0 = [127 0 7]/255;
C1 = [255 0 0]/255;
C2 = [255 97 0]/255;
C3 = [255 150 0]/255;
C4 = [255 182 0]/255;
C5 = [255 220 0]/255;
C6 = [255 255 0]/255;
C7 = [214 255 0]/255;
C8 = [173 255 0]/255;
C9 = [123 255 0]/255;
C10 = [0 255 123]/255;
C11 = [0 255 222]/255;
C12 = [0 223 255]/255;
C13 = [0 166 255]/255;
C14 = [0 0 255]/255;
C15 = [0 20 96]/255;
m = [C15; C14; C13; C12; C11; C10; C9; C8; C7; C6; C5; C4; C3; C2; C1; C0];
colormap(m)
axi = [-16 0];
caxis(axi);
axis tight; axis equal;
axis([xlim,ylim]);
colorbar;
plot(bp(:,1),bp(:,2),'k');
plot(bs(:,1),bs(:,2),'k');
%dpx = [.0588,.0880,.0843,.0551];
%dpy = [.3949,.3910,.3632,.3671];
%plot(dpx(1:2),dpy(1:2),'k');
%plot(dpx(3:4),dpy(3:4),'k');
%LeftArc = load('LeftArc.txt');
%x = LeftArc(:,2);
%y = LeftArc(:,1);
%plot(x,y,'k');
%RightArc = load('RightArc.txt');
%x = RightArc(:,2);
%y = RightArc(:,1);
%plot(x,y,'k');
%x = .005*cos([0:10:360]*(pi/180));
%y = .005*sin([0:10:360]*(pi/180));

```

```

%xR = x + .09;
%yR = y + .3765;
%xL = x + .058;
%yL = y + .3811;
%plot(xR,yR,[0 0 0]);
%plot(xL,yL,[0 0 0]);
% LeftArcXo = .5*(dpx(1)+dpx(4));
% LeftArcYo = .5*(dpy(1)+dpy(4));
% RightArcXo = .5*(dpx(2)+dpx(3));
% RightArcYo = .5*(dpy(2)+dpy(3));
% %Left Arc
% LeftArcRx = LeftArcXo - dpx(1);
% LeftArcRy = dpy(1) - LeftArcYo;
% LeftArcR = sqrt(LeftArcRx^2 + LeftArcRy^2);
% %Right Arc
% RightArcRx = dpx(3) - RightArcXo;
% RightArcRy = RightArcYo - dpy(3);
% RightArcR = sqrt(RightArcRx^2 + RightArcRy^2);
toc

```

B3. DPC.m – Contour plot of temperature along tip

```

function DPC(filename);
%Jesse Christophel | 12-5-02 | Pratt & Whitney
%-----
%This file takes computational data for a blade
%TIP only in 3-column format [X Y Z] where Z is
%dependent variable.
%
%Call the function with the file name you want.
%Example DPC('new_9mm_dp_high.txt')
dude = load(filename);
x1 = dude(:,1);
y1 = dude(:,2);
n1 = dude(:,3);
x = linspace(min(x1),max(x1),500);
y = linspace(min(y1),max(y1),1000);
[X,Y,N] = griddata(x1,y1,n1,x,y);
R_b_suc = load('SuctionCoords.txt');
R_b_pre = load('PressureCoords.txt');
R_b_suc = sortrows(R_b_suc,1);
R_b_pre = sortrows(R_b_pre,1);
R_b_suc(:,2) = R_b_suc(:,2) + 0.3797;
R_b_pre(:,2) = R_b_pre(:,2) + 0.3797;
bp = R_b_pre;
bs = R_b_suc;
bp_cut = bp(1:(end-10),:);
PS_pp = spline(bp_cut(:,1),bp_cut(:,2));
%Needed only for TIP files
BladeX = find(min(bp_cut(:,1)) <= x & x <= max(bp_cut(:,1)));
BladeX_Val = x(BladeX);
PS = ppval(PS_pp,BladeX_Val);
for i=1:length(BladeX)

```

```

    ErrInd = find(y < PS(i));
    if length(ErrInd) > 0;
        N(ErrInd,BladeX(i)) = NaN;
    end
end
C0 = [255 0 0]/255;
C1 = [255 43 0]/255;
C2 = [255 85 0]/255;
C3 = [255 128 0]/255;
C4 = [255 170 0]/255;
C5 = [255 212 0]/255;
C6 = [255 255 0]/255;
C7 = [191 255 0]/255;
C8 = [128 255 0]/255;
C9 = [64 255 0]/255;
C10 = [0 255 0]/255;
C11 = [0 255 64]/255;
C12 = [0 255 128]/255;
C13 = [0 255 191]/255;
C14 = [0 255 255]/255;
C15 = [0 204 255]/255;
C16 = [0 153 255]/255;
C17 = [0 102 255]/255;
C18 = [0 51 255]/255;
C19 = [0 0 255]/255;
m = [C0; C1; C2; C3; C4; C5; C6; C7; C8; C9; C10; C11; C12; C13; C14; C15; C16; C17; C18; C19];
[c,ch,cf] = contourf(X,Y,N,20); axis equal;
hold on; plot(R_b_suc(:,1),R_b_suc(:,2),'k',R_b_pre(:,1),R_b_pre(:,2),'k');
set(ch,'LineStyle', 'none');
axi = [0 1];
caxis(axi);
colormap(m)
colorbar;
axis equal;
axis off;

```

B4. Sample Fluent Journal File

```
/Creating ss and ps planes in fluent ssl
(cx-gui-do cx-activate-item "MenuBar*SurfaceMenu*Plane...")
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry1(x0)" '( 0.001))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry2(y0)" '( 0.3828))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry3(z0)" '( -0.276))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry4(x1)" '( -0.1383))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry5(y1)" '( 0.4385))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry6(z1)" '( -0.276))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry7(x2)" '( -0.1383))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry8(y2)" '( 0.4385))
(cx-gui-do cx-set-real-entry-list "Plane Surface*Frame2(Points)*Table1*RealEntry9(z2)" '( 0))
(cx-gui-do cx-set-toggle-button "Plane Surface*Frame1*Frame1(Options)*ToggleBox1(Options)*CheckBox3(Bounded)" #f)
(cx-gui-do cx-activate-item "Plane Surface*Frame1*Frame1(Options)*ToggleBox1(Options)*CheckBox3(Bounded)")
(cx-gui-do cx-set-toggle-button "Plane Surface*Frame1*Frame1(Options)*ToggleBox1(Options)*CheckBox4(Sample Points)" #f)
(cx-gui-do cx-activate-item "Plane Surface*Frame1*Frame1(Options)*ToggleBox1(Options)*CheckBox4(Sample Points)")
(cx-gui-do cx-set-integer-entry "Plane Surface*Frame1*Frame2*Frame1(Sample Density)*IntegerEntry1(Edge 1)" 29)
(cx-gui-do cx-set-integer-entry "Plane Surface*Frame1*Frame2*Frame1(Sample Density)*IntegerEntry2(Edge 2)" 27)
(cx-gui-do cx-set-text-entry "Plane Surface*TextEntry3(New Surface Name)" "ss1_sample")
(cx-gui-do cx-activate-item "Plane Surface*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-activate-item "Plane Surface*PanelButtons*PushButton1(Cancel)")
/(cx-gui-do cx-activate-item "MenuBar*WriteSubMenu*Stop Journal")
```

B5. LongitudinalAvgNew.m – Computes pitchwise-averaged data

```
function LongitudinalAvgNew(filename,tol,DimlessIncrement,fileout)
%=====
%
% Function Name: LongitudinalAvgNew takes data from a file, calculates sampling
%               locations, and averages the data that falls within an a
%               tolerable distance of the sampling points
%
% Calling Sequence: LongitudinalAvgNew(filename,tol,DimlessIncrement)
%
% Inputs: filename - Data file entered as a string e.g. 'SampleData.txt'
%        tol       - Acceptable deviation from a sampling location in
%                   the non normalized units consistent with data file
%        DimlessIncrement - Dimensionless distance between sampling locations
%        fileout    - Data file to create/write to - entered as a string
%                   e.g. 'SampleData.txt'
%
% Outputs: Plots of Data points and averages at sampling locations
%=====
tic
clc
format compact
format long
close all
Mat = load(filename);
% Normalizing Values
Chord = .35; %axial chord for PW tip
Pitch = .4297; %pitch for PW tip
tolNorm = tol/Chord;
Mat = sortrows(Mat,[1 2]);
% Generate matrix of normalized locations and Eta
MatNorm = [Mat(:,1)/Chord, Mat(:,2)/Pitch, Mat(:,3)];
% Display range of independent variable and range of Averaging Pts
disp(['Min x/C = ',num2str(min(MatNorm(:,1)))])
disp(['Max x/C = ',num2str(max(MatNorm(:,1)))])
disp(' ')
% StartPt = fix(min(MatNorm(:,1))/DimlessIncrement) * DimlessIncrement; %fix command has problems
% with rounding #'s
% EndPt = fix(max(MatNorm(:,1))/DimlessIncrement) * DimlessIncrement; %round seems to work better
StartPt = round(min(MatNorm(:,1))/DimlessIncrement) * DimlessIncrement;
EndPt = round(max(MatNorm(:,1))/DimlessIncrement) * DimlessIncrement;
disp(['Min Averaging x/C = ',num2str(StartPt)])
disp(['Max Averaging x/C = ',num2str(EndPt)])
disp(' ')
% Plot of all imported Data Points
figure
plot(MatNorm(:,1),MatNorm(:,2),'.')
title('Plot of Data Points')
xlabel('x/C')
ylabel('y/P')
axis equal
axis([0 1 0 1])
grid on
BinLocs = StartPt:DimlessIncrement:EndPt;
```



```

NumBins = length(BinLocs);
clear Mat filename Chord Pitch tol StartPt EndPt DimlessIncrement
% Initialize Bins
for i = 1:NumBins
    VarDefine = ['Bin', int2str(i), '= []:'];
    eval(VarDefine)
end
clear VarDefine i
% Sort the data into appropriate bins
% Add one to account for endpoint in BinLocs vector
for i = 1:NumBins
    BinLocation = BinLocs(i);
    BinPass = ['Bin',int2str(i),'=BinPlace(MatNorm,BinLocation,tolNorm);'];
    eval(BinPass)
end
clear i BinLocation BinPass MatNorm
% Plot of unfiltered Data "Bins"
figure
for i = 1:NumBins
    BinNum = eval(['Bin',num2str(i)]);
    EmptyTest = isempty(BinNum);
    if EmptyTest == 0
        BinPlot(BinNum)
    end
end
title('Unfiltered Data "Bins"')
xlabel('x/C')
ylabel('y/P')
axis equal
axis([0 1 0 1])
grid on
clear i
SortHist = [];
AvgEta = [];
% Filter data to avoid duplicate points when integrating
figure
% Counter for bins that are plottable
FilledBins = [];
j = 1;
for i = 1:NumBins
    BinNum = eval(['Bin',num2str(i)]);
    if length(BinNum) > 2
        [BinNum, Unfil, Fil, DupNum, XLoc] = DataFilter(BinNum,BinLocs(i));
        if length(BinNum) > 0
            % Plot of filtered Data "Bins"
            BinPlot(BinNum)
            AvgEta(j) = 1/(BinNum(end,2) -
BinNum(1,2))*trapz(BinNum(:,2),BinNum(:,3));
            kept = 1;
            SortHist(i,:) = [XLoc, AvgEta(j), Unfil, Fil, DupNum];
            FilledBins(j) = BinLocs(i);
            j = j + 1;
        else
            kept = 0;
            SortHist(i,:) = [XLoc, NaN, Unfil, Fil, DupNum];
        end
    end
end

```

```

else
    kept = 0;
    SortHist(i,:) = [BinLocs(i), NaN, 0, 0, 0];
end
eval(['clear Bin',num2str(i),';'])
end
EmptyBins = length(BinLocs) - length(FilledBins);
if EmptyBins > 0
    disp([int2str(EmptyBins), ' bin(s) were not plotted due to insufficient data'])
    disp(' ')
end
if length(FilledBins) ~= length(AvgEta)
    disp('There are not an equal number of Data Bins and Avg Eta points')
end
title('Filtered Data "Bins"')
xlabel('x/C')
ylabel('y/P')
axis equal
axis([0 1 0 1])
grid on
% Table of filtering history
fprintf(' x/C\t Avg\t UnFilt\t Filter\t Dup\n')
fprintf('\t\t Eta\t Number\t Number\t Number\n')
fprintf('%4.3f\t %4.3f\t %3.0f\t %3.0f\t %3.0f\n',SortHist')
fprintf('\r')
% Plot of Longitudinally averaged Eta
figure
plot(FilledBins, AvgEta,'.-')
title('Longitudinally Averaged Adiabatic Effectiveness, \eta')
xlabel('x/C')
ylabel('\eta_{avg}')
axis([0 1 0 1])
grid on;
if nargin == 4
    EtaData = [FilledBins;AvgEta];
    fid = fopen(fileout,'w');
    fprintf(fid,'%x/C\t Eta\n');
    fprintf(fid,'%3.2f\t %4.3f\n',EtaData);
    fclose(fid);
end
toc
%===== SubFunction BinPlace - Find Data lying within tolerance of BinPt
function BinData = BinPlace(MatNorm,BinLocation,tolNorm)
BinData = [];
k = 1;
for j = 1:length(MatNorm)
    if abs(MatNorm(j,1)-BinLocation) <= tolNorm
        BinData(k,:) = MatNorm(j,:);
        k = k + 1;
    elseif MatNorm(j,1) > BinLocation
        if length(BinData) > 0
            break
        end
    end
end
end
end

```

```

if length(BinData) > 0
    BinData = sortrows(BinData,[2 1]);
end
%===== SubFunction BinPlot to create plots of Data Sorted into "Bins" =====%
function BinPlot(BinNum)
plot(BinNum(:,1),BinNum(:,2),'')
hold on
%===== SubFunction DataFilter =====%
function [FiltMat, UnFilLength, FilLength, DupNum,DimlessXLoc] = DataFilter(Mat,DimlessXLoc)
% FiltMat - Matrix containing filtered data
% UnFilLength - Number of data points before filtration
% FilLength - Number of data points after filtration
% DupNum - Number of discarded points
% DimlessXLoc - BinLocation
DimlessXLoc = DimlessXLoc;
UnFilLength = length(Mat(:,1));
FiltMat = [DimlessXLoc, Mat(1,2:3)];
DupNum = 0;
m = 2; % Counter to track length of Filtered Matrix
for n = 2:UnFilLength
    if Mat(n,2)-Mat(n-1,2) == 0
        Dist1 = Mat(n-1,1) - DimlessXLoc;
        Dist2 = Mat(n,1) - DimlessXLoc;
        DupNum = DupNum + 1;
        switch sign(Dist1) + sign(Dist2)
            case 0
                Dist1 = abs(Dist1);
                Dist2 = abs(Dist2);
                TotDist = Dist1 + Dist2;
                if TotDist > 0
                    Avg = (Dist1*Mat(n,3) + Dist2*Mat(n-1,3))/TotDist;
                    FiltMat(end,:) = [DimlessXLoc,Mat(n,2),Avg];
                else
                    Avg = (Mat(n,3) + Mat(n-1,3))/2;
                    FiltMat(end,:) = [DimlessXLoc,Mat(n,2),Avg];
                    % Message indicating duplicate data
                    DupMat = [Mat(n-1,:);Mat(n,:)];
                    disp(['There is duplicate data in line ',int2str(n),' of the input file'])
                    fprintf('x/C\t\t y/P\t Eta\n');
                    fprintf('%4.3f\t %4.3f\t %4.3f\n',DupMat)
                    fprintf('\r');
                end
            otherwise
                Dist1 = abs(Dist1);
                Dist2 = abs(Dist2);
                if Dist1 > Dist2
                    FiltMat(end,:) = [DimlessXLoc,Mat(n,2:3)];
                else
                    FiltMat(end,:) = [DimlessXLoc,Mat(n-1,2:3)];
                end
            end
        end
        FiltMat(m,:) = [DimlessXLoc, Mat(n,2:3)];
        m = m + 1;
    end
end
end

```

```

FilLength = length(FiltMat);
if DupNum + FilLength ~= UnFilLength
    disp(['Data may have been lost from x/C = ',int2str(DimlessXLoc),' bin. Review summary table.'])
    disp(' ')
end

```

Appendix C: Tip Secondary Flow – Pressure side and Suction side planes.

Thirteen planes were defined around the blade tip to study secondary flow patterns throughout the turbine passage. A total of seven suction side planes and six pressure side planes were positioned normal to the blade surface and are shown in Figure C0. A detailed discussion concerning the methodologies behind this secondary flow visualization technique is presented in Section 4.5 with several planes shown in Chapter 5. The following appendix contains data from twelve different cases which include cases with a:

1. small gap and a flat tip,
2. large gap and a flat tip,
3. small gap and a dirt purge cavity,
4. large gap and a dirt purge cavity,
5. small gap and 0.19% dirt purge blowing,
6. large gap and 0.19% dirt purge blowing,
7. small gap and 0.29% dirt purge blowing,
8. large gap and 0.29% dirt purge blowing,
9. small gap and 1.0% microcircuit and dirt purge blowing,
10. large gap and 1.0% microcircuit and dirt purge blowing,
11. small gap and 1.5% microcircuit and dirt purge blowing, and
12. large gap and 1.5% microcircuit and dirt purge blowing.

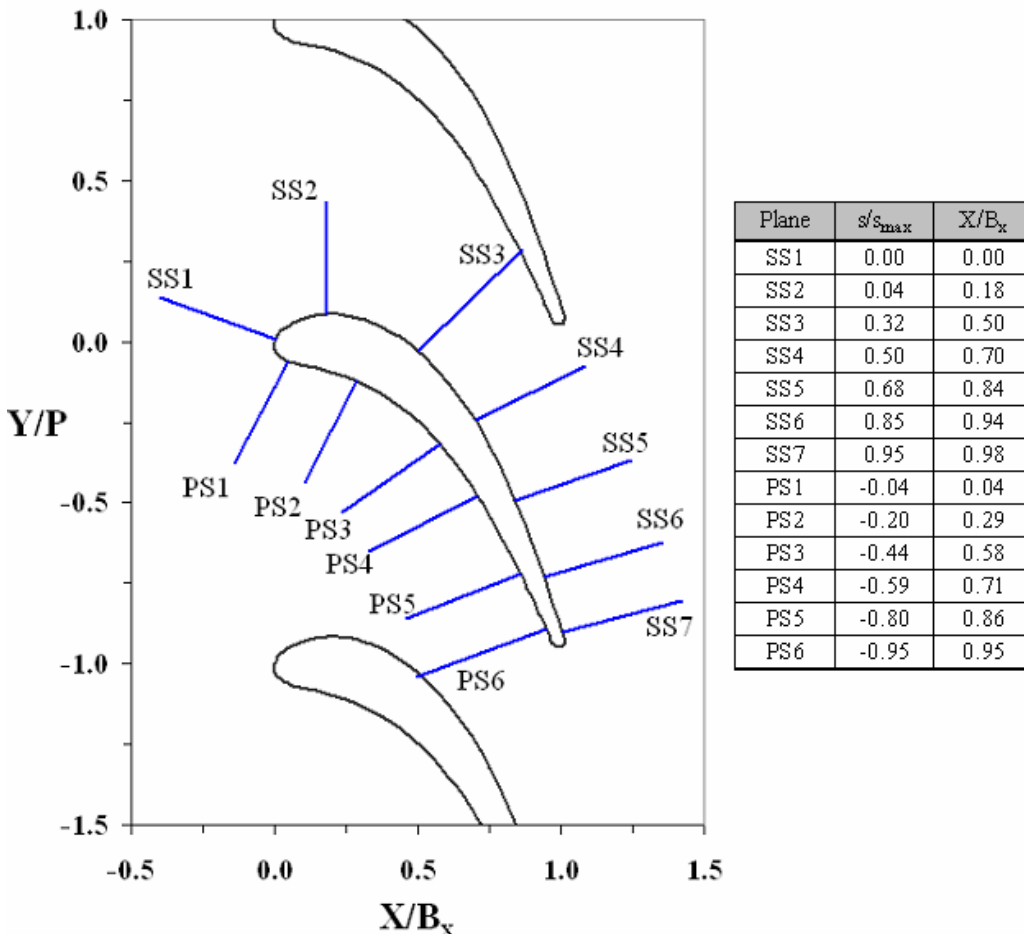


Figure C0. Location of secondary flow planes around the tip geometry

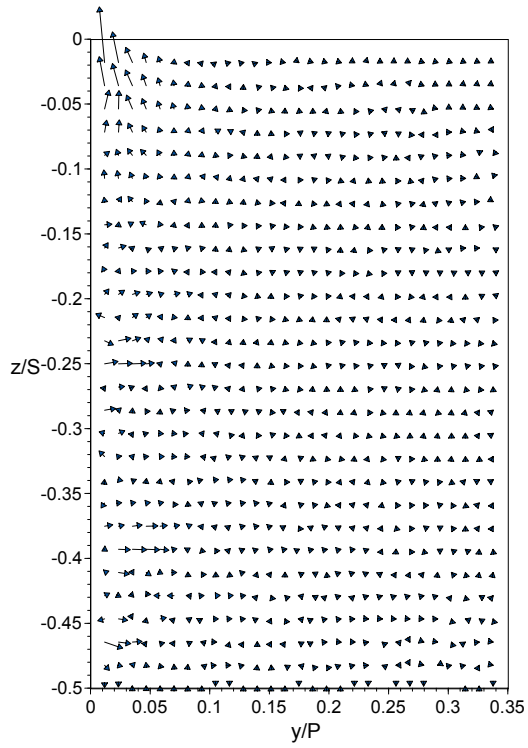


Figure C1. SS1 - Small tip gap, flat tip.

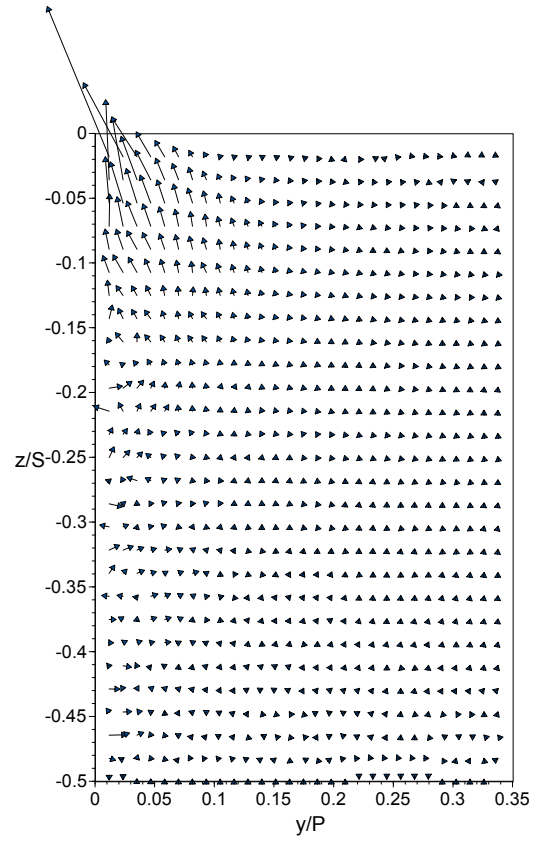


Figure C2. SS1 - Large tip gap, flat tip.

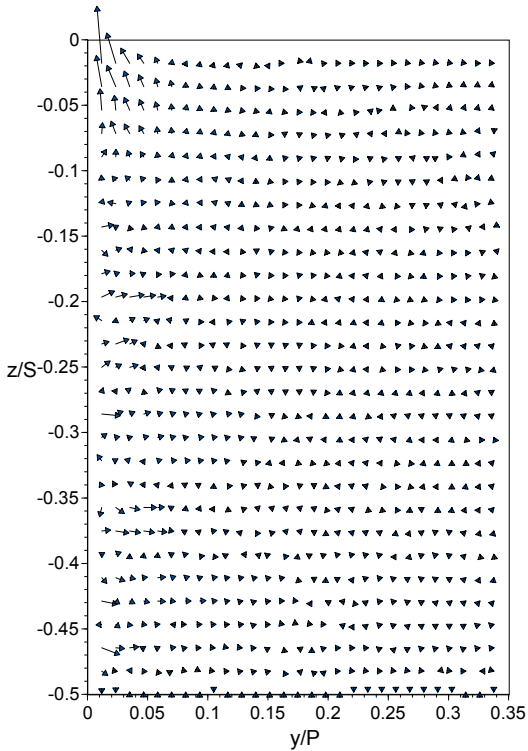


Figure C3. SS1 - Small tip gap, dirt purge cavity, no cooling.

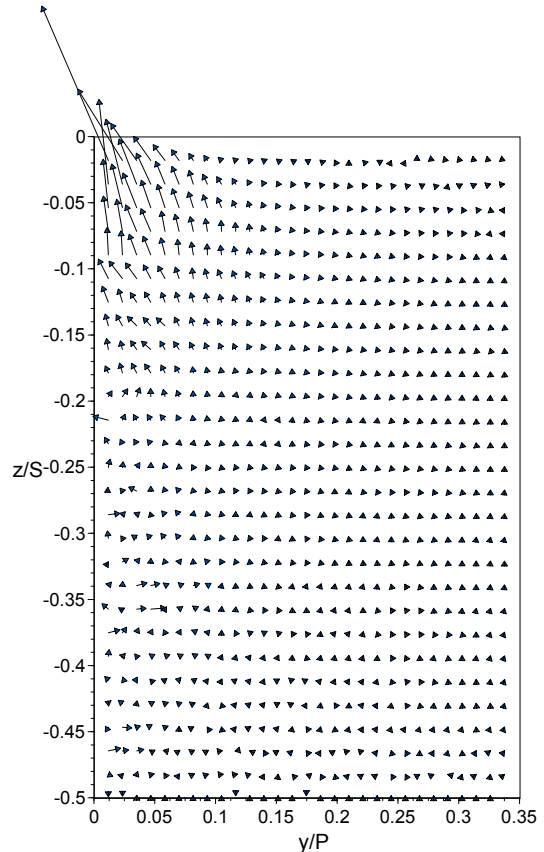


Figure C4. SS1 - Large tip gap, dirt purge cavity, no cooling.

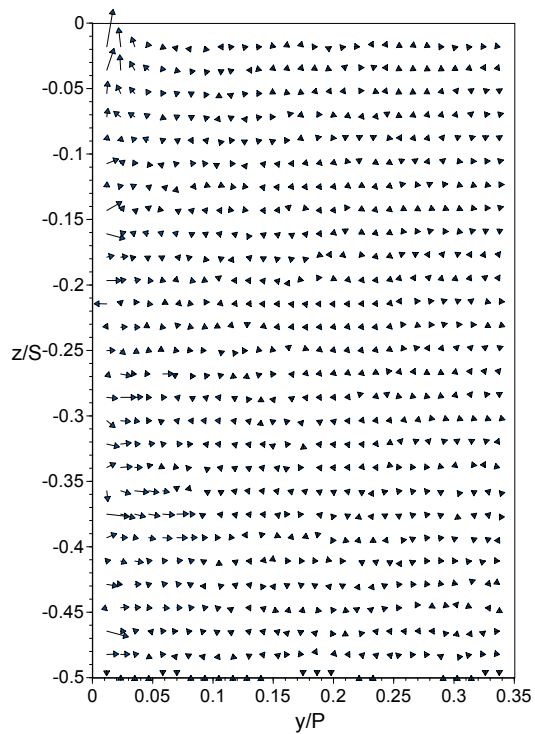


Figure C5. SS1 - Small tip gap, 0.19% dirt purge cooling.

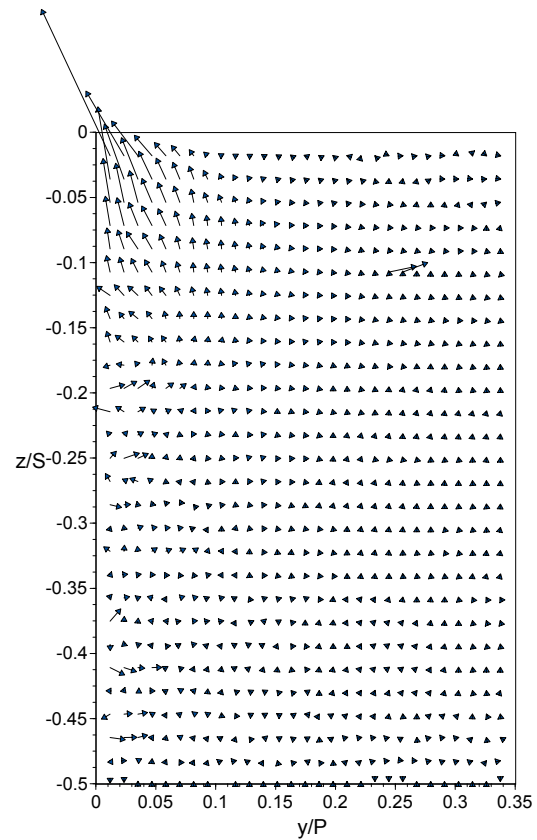


Figure C6. SS1 - Large tip gap, 0.19% dirt purge cooling.

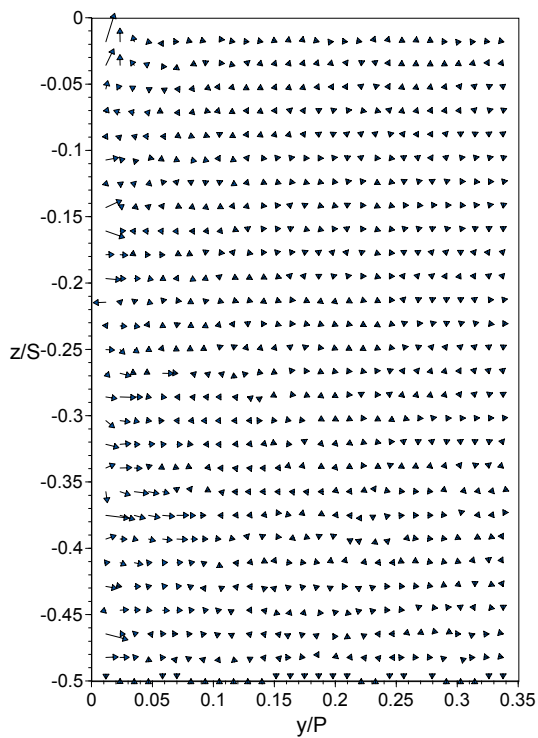


Figure C7. SS1 - Small tip gap, 0.29% dirt purge cooling.

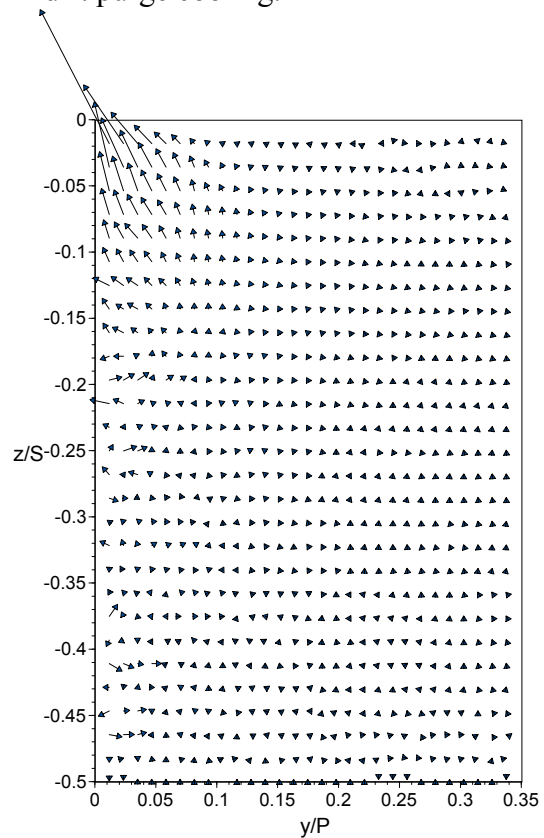


Figure C8. SS1 - Large tip gap, 0.29% dirt purge cooling.

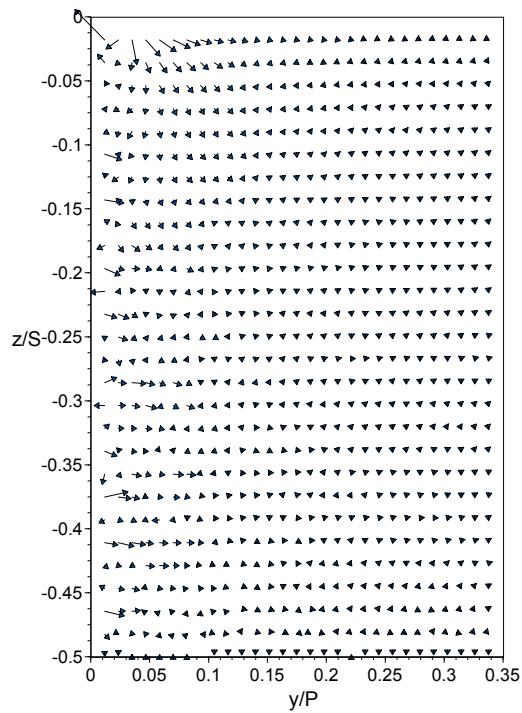


Figure C9. SS1 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

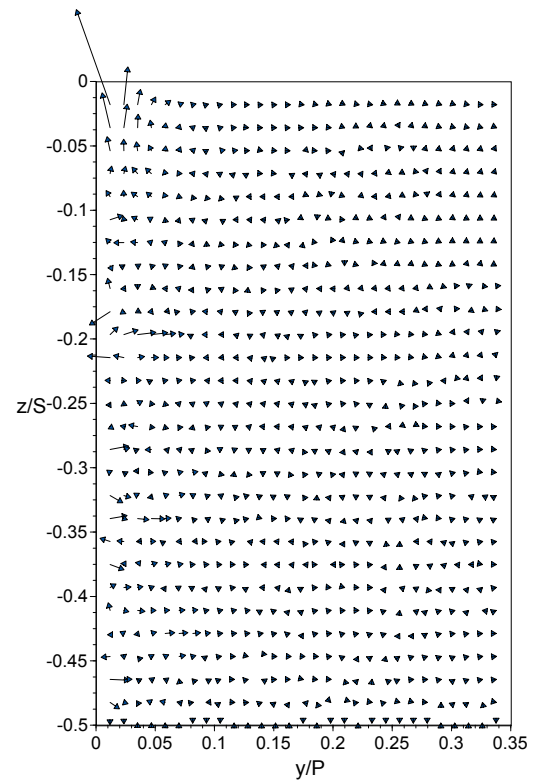


Figure C10. SS1 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

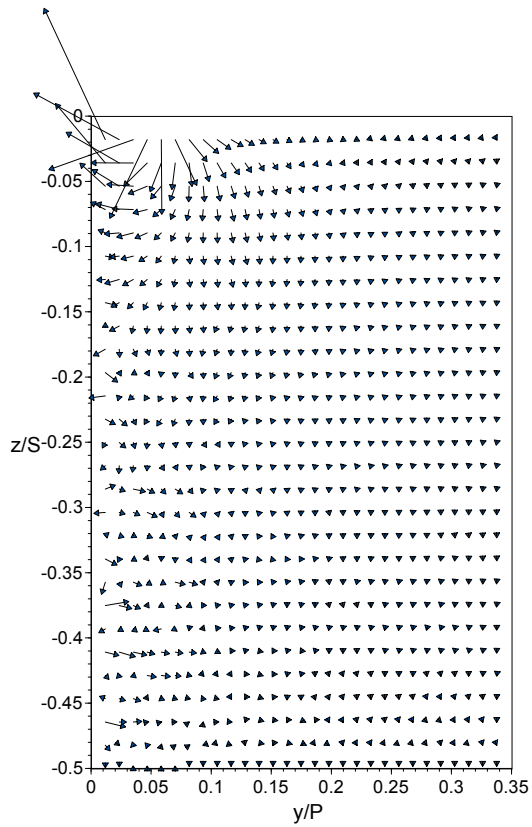


Figure C11. SS1 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

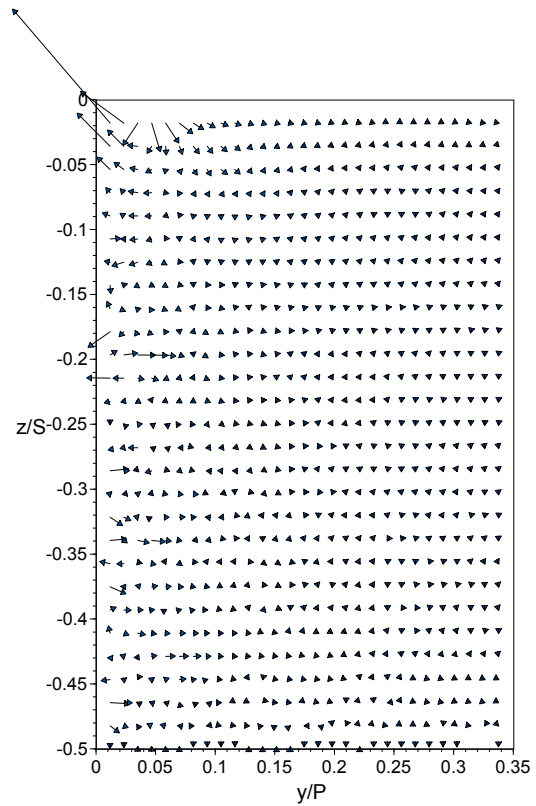


Figure C12. SS1 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

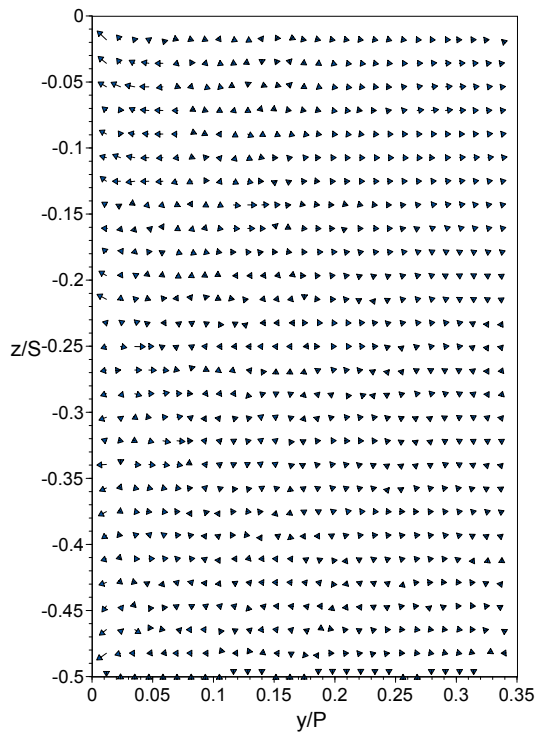


Figure C13. SS2 - Small tip gap, flat tip.

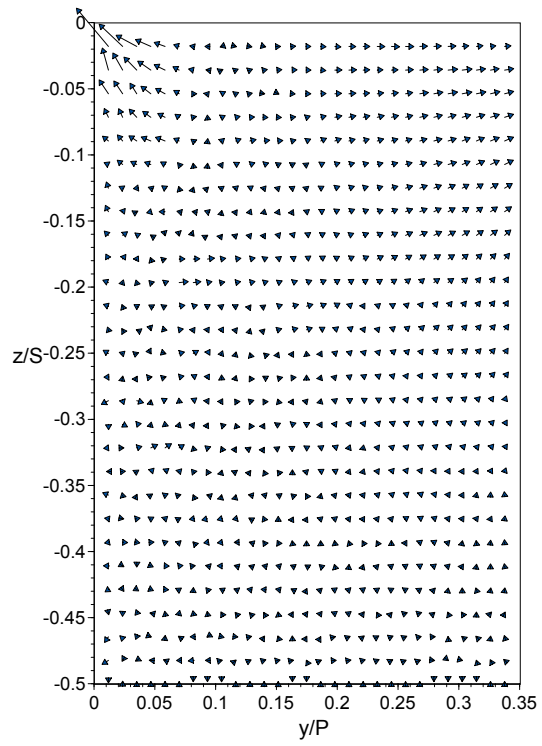


Figure C14. SS2 - Large tip gap, flat tip.

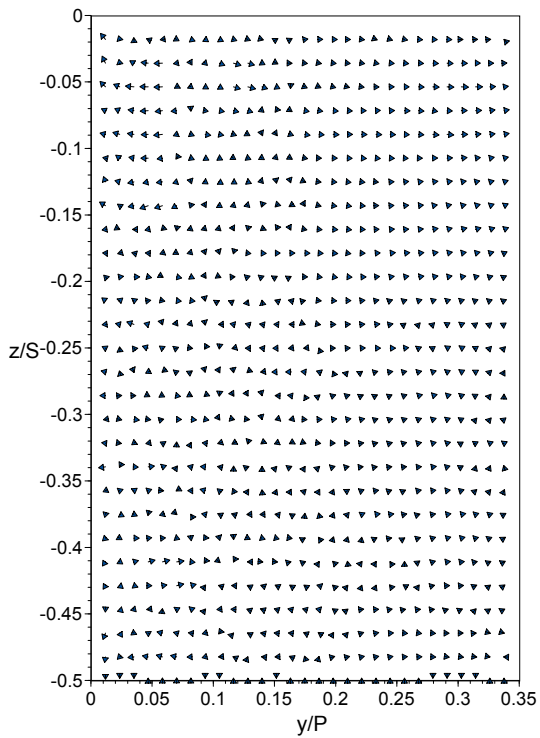


Figure C15. SS2 - Small tip gap, dirt purge cavity, no cooling.

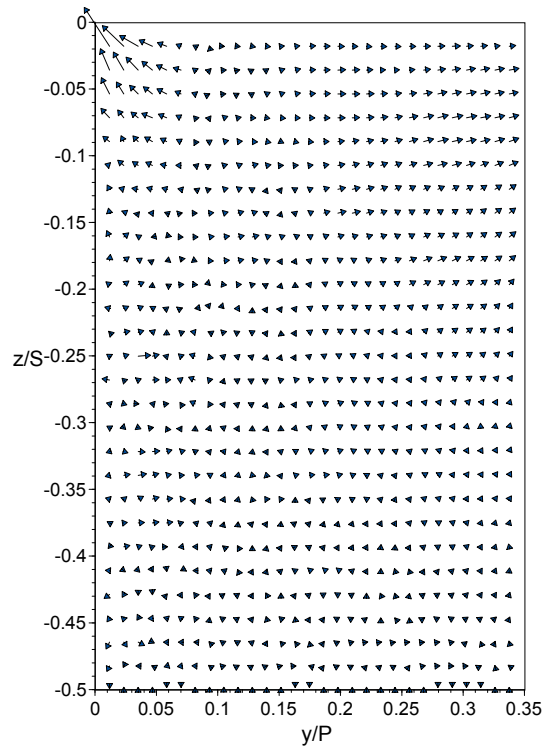


Figure C16. SS2 - Large tip gap, dirt purge cavity, no cooling.

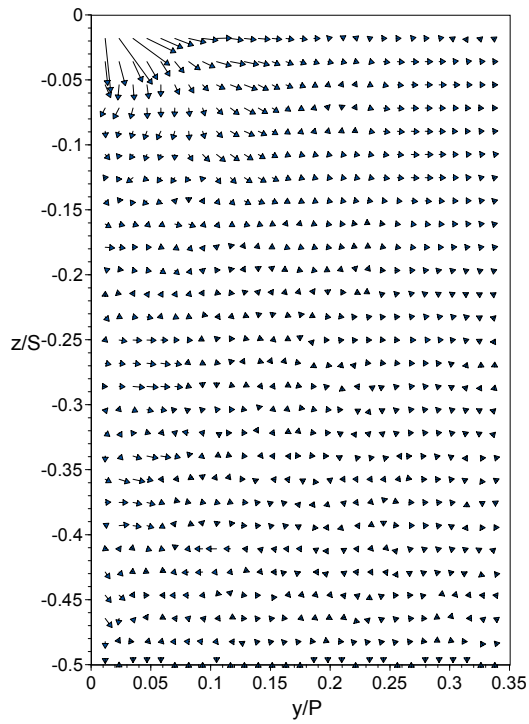


Figure C17. SS2 - Small tip gap, 0.19%
dirt purge cooling.

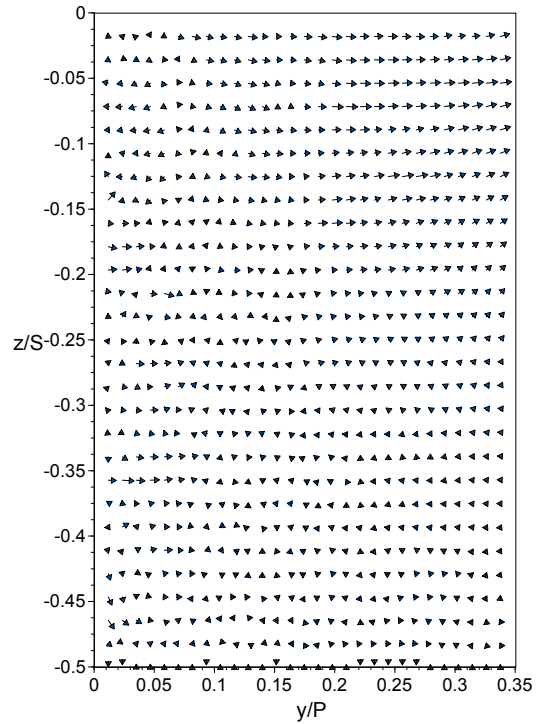


Figure C18. SS2 - Large tip gap, 0.19%
dirt purge cooling.

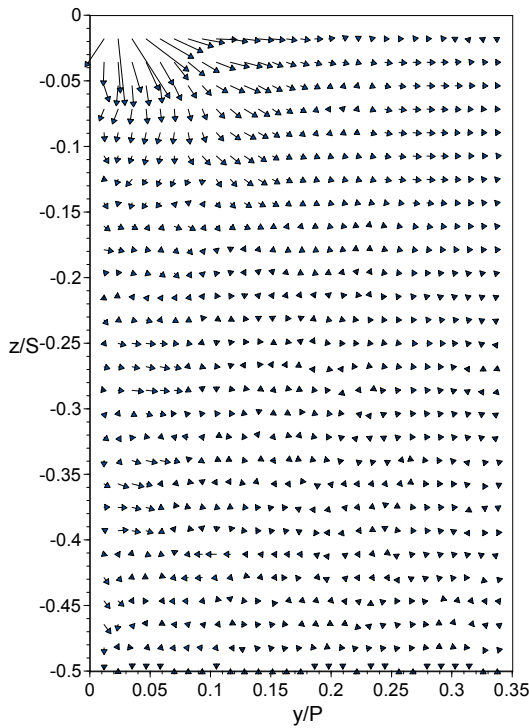


Figure C19. SS2 - Small tip gap, 0.29%
dirt purge cooling.

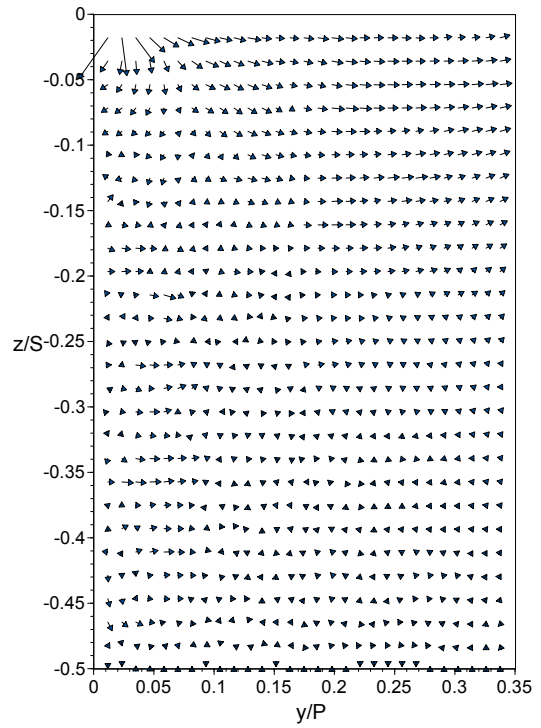


Figure C20. SS2 - Large tip gap, 0.29%
dirt purge cooling.

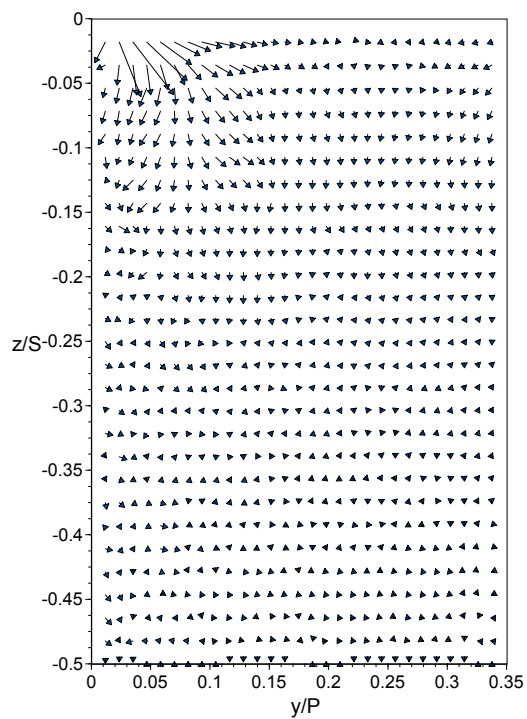


Figure C21. SS2 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

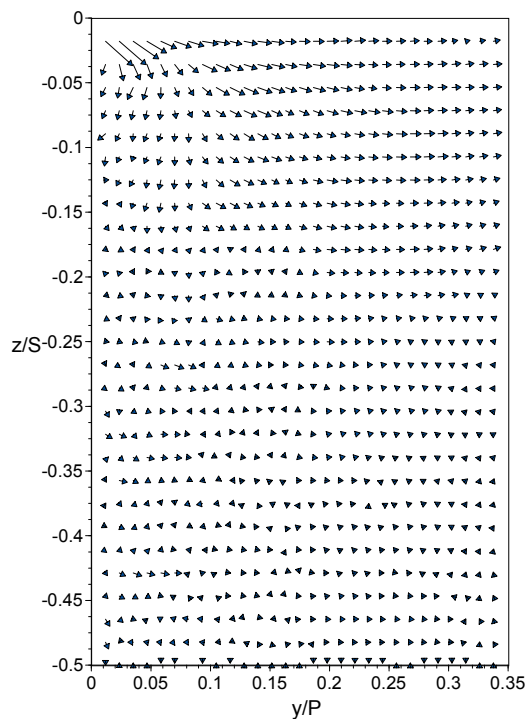


Figure C22. SS2 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

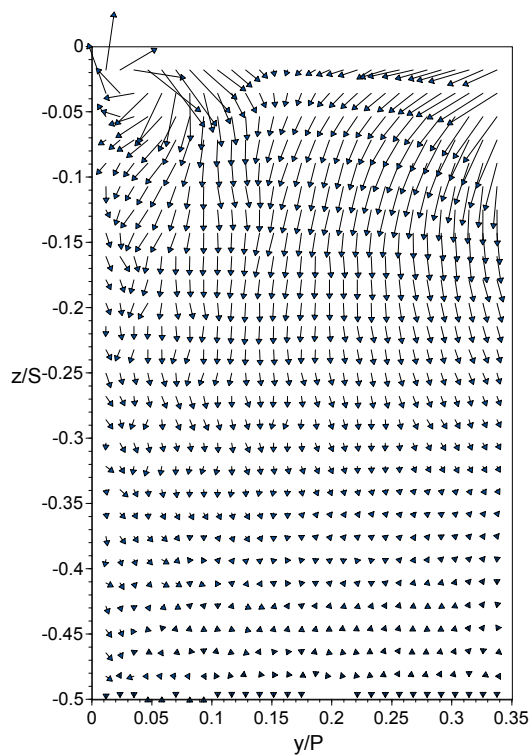


Figure C23. SS2 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

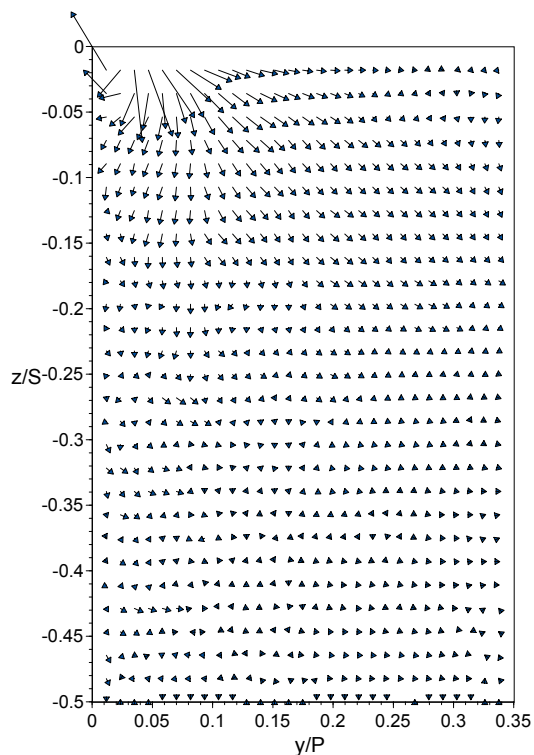


Figure C24. SS2 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

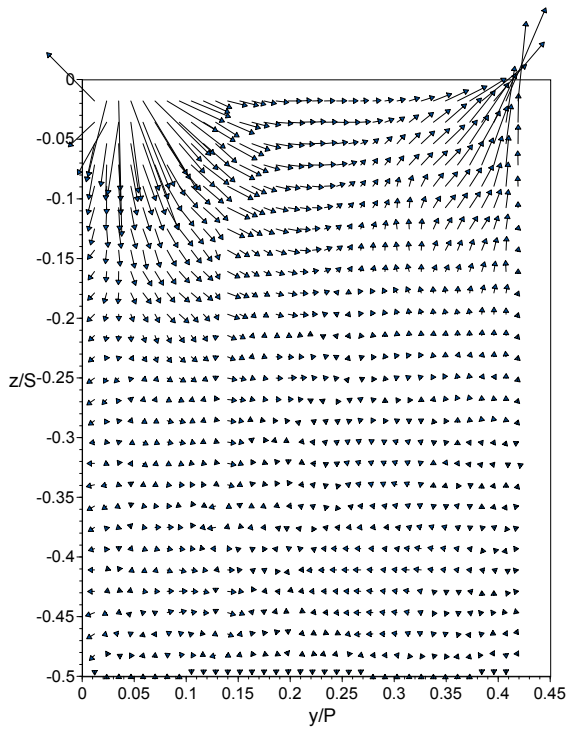


Figure C25. SS3 - Small tip gap, flat tip.

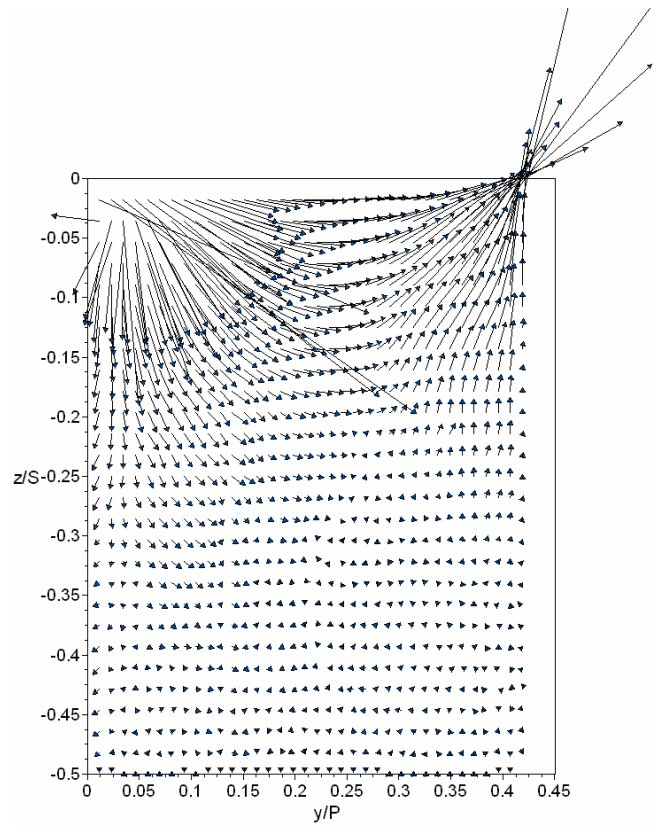


Figure C26. SS3 - Large tip gap, flat tip.

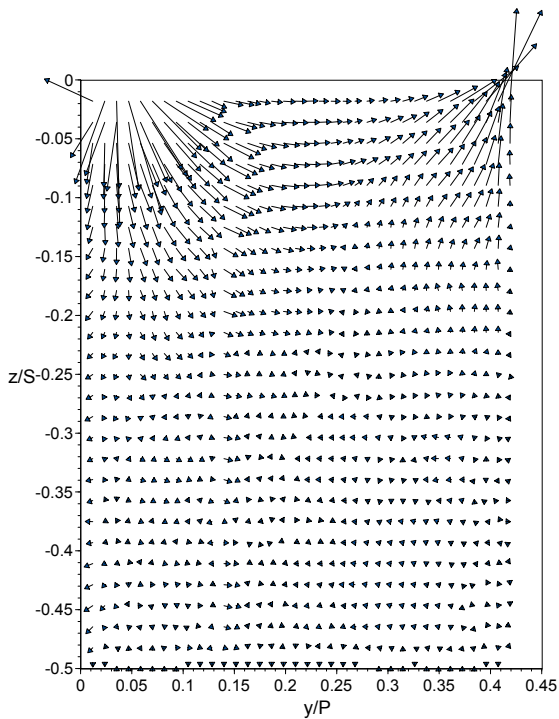


Figure C27. SS3 - Small tip gap, dirt purge cavity, no cooling.

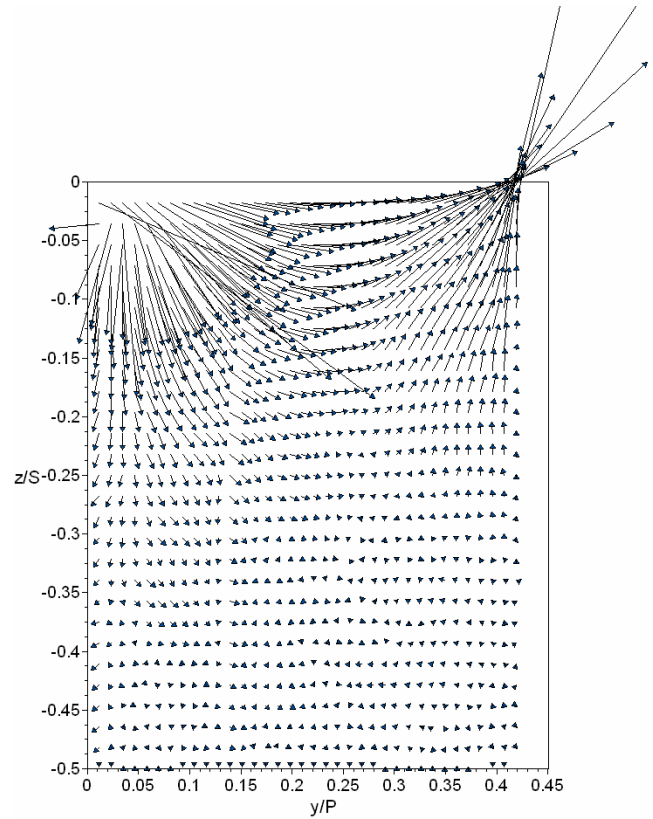


Figure C28. SS3 - Large tip gap, dirt purge cavity, no cooling.

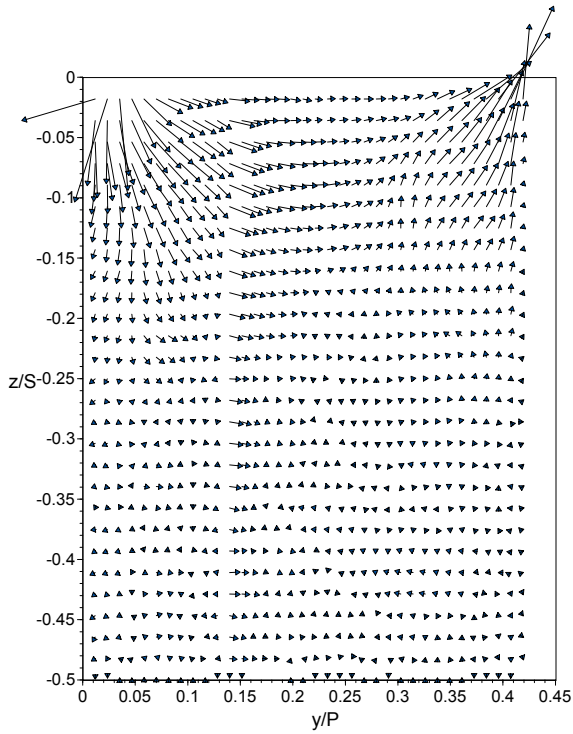


Figure C29. SS3 Small tip gap, 0.19% dirt purge cooling.

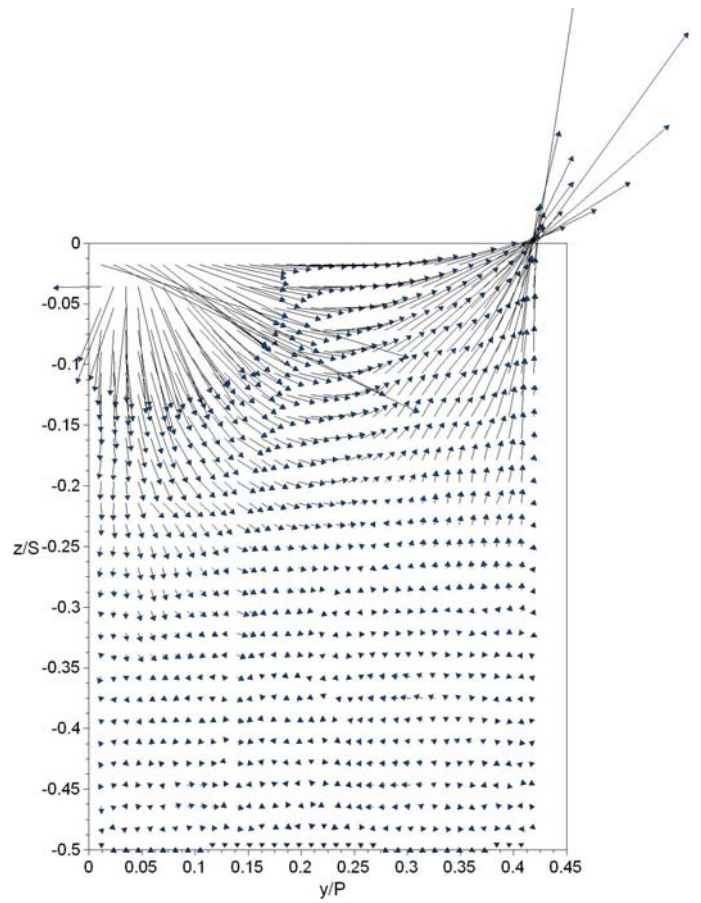


Figure C30. SS3 - Large tip gap, 0.19% dirt purge cooling.

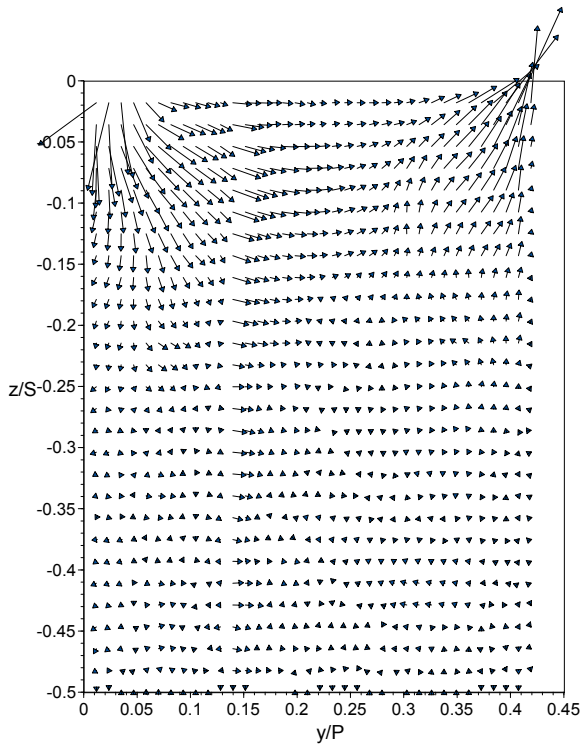


Figure C31. SS3 - Small tip gap, 0.29% dirt purge cooling.

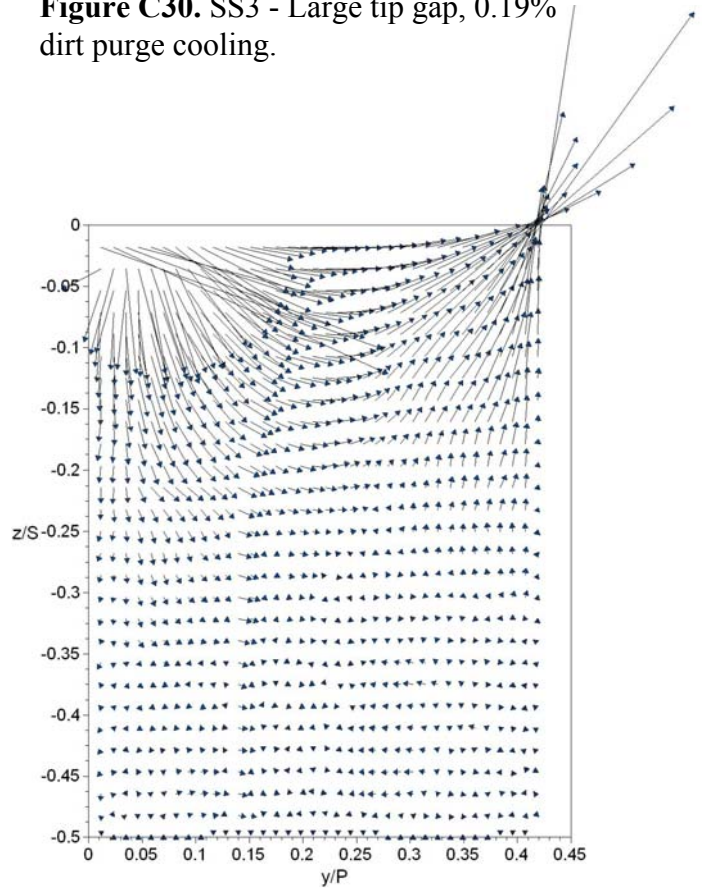


Figure C32. SS3 - Large tip gap, 0.29% dirt purge cooling.

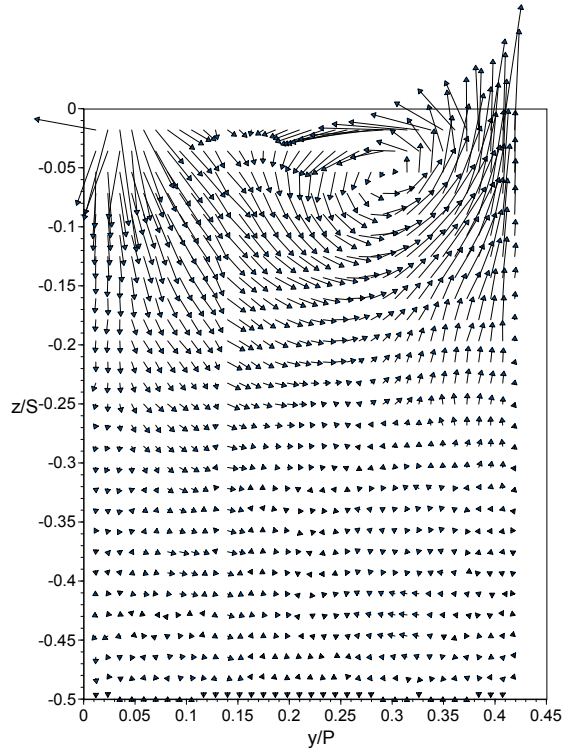


Figure C33. SS3 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

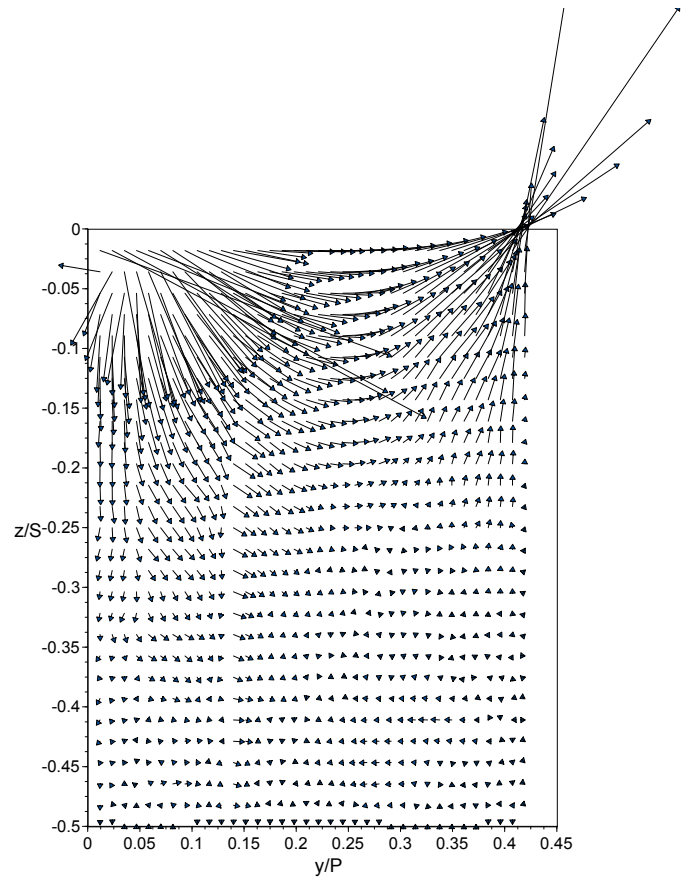


Figure C34. SS3 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

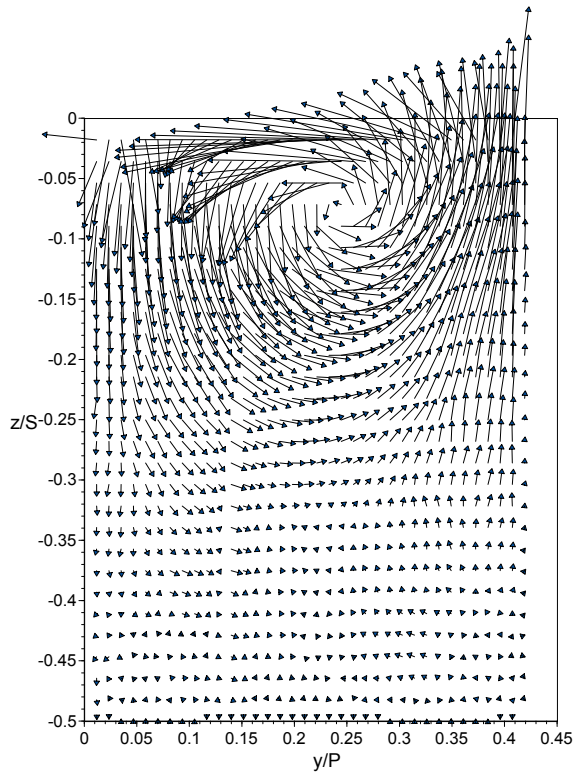


Figure C35. SS3 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

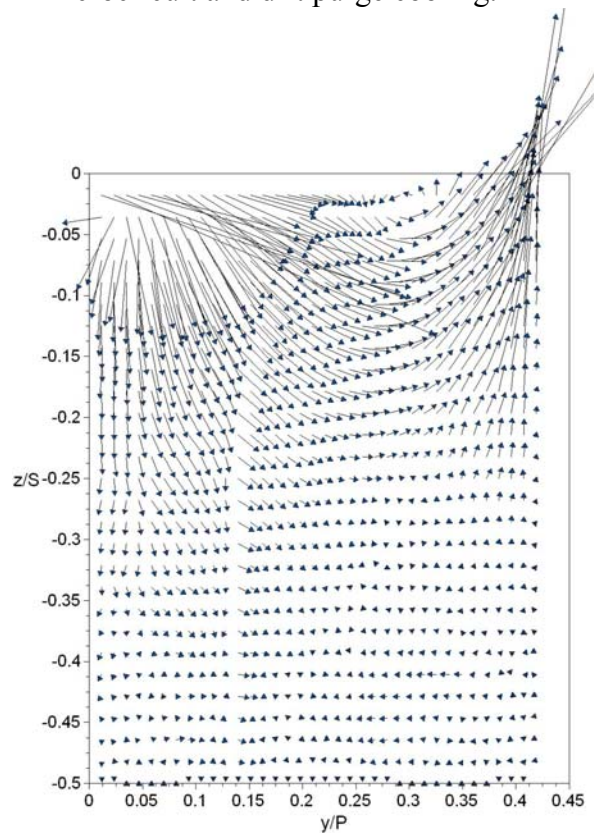


Figure C36. SS3 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

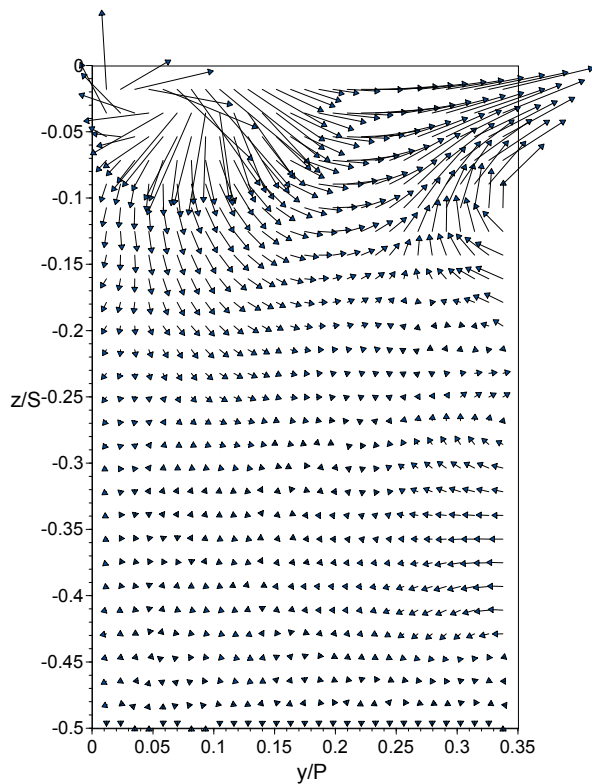


Figure C37. SS4 - Small tip gap, flat tip.

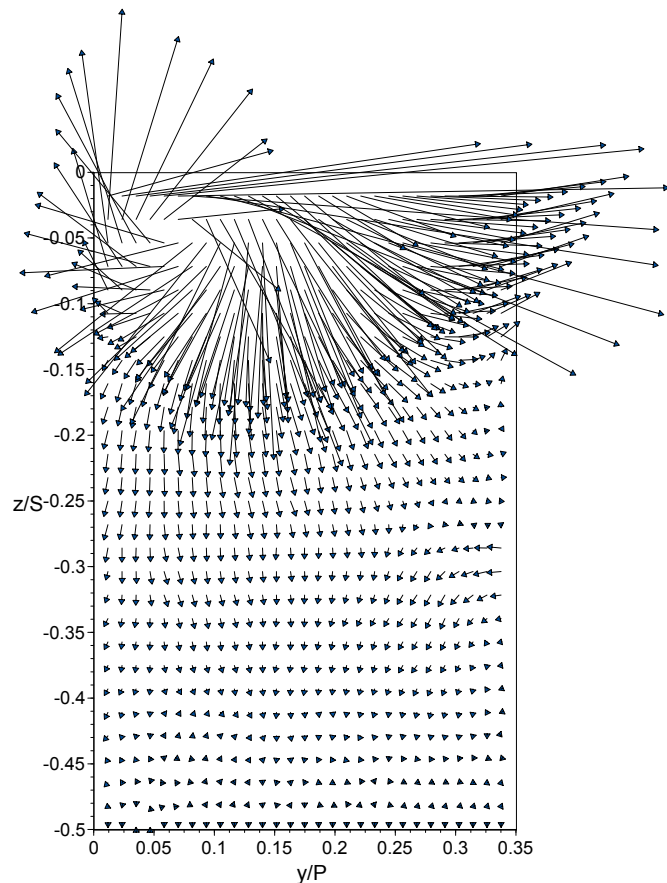


Figure C38. SS4 - Large tip gap, flat tip.

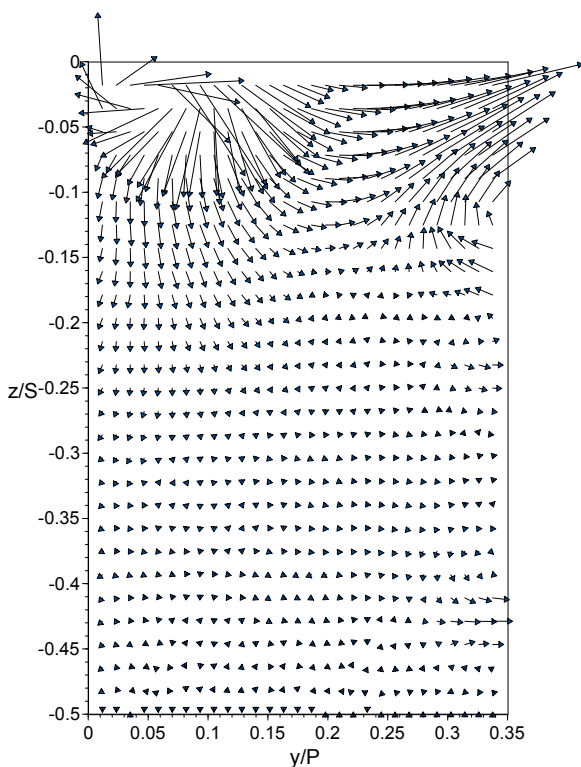


Figure C39. SS4 - Small tip gap, dirt purge cavity, no cooling.

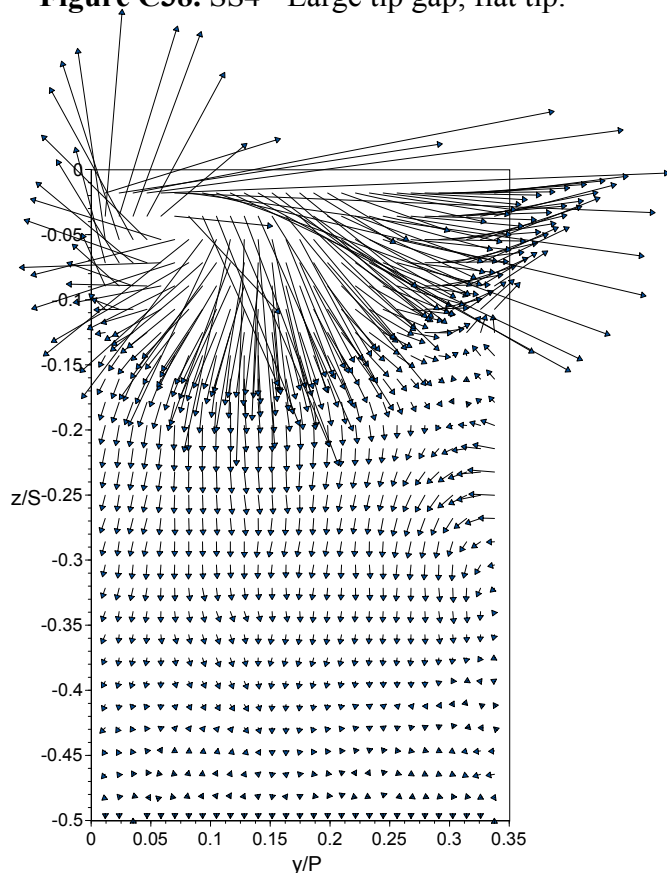


Figure C40. SS4 - Large tip gap, dirt purge cavity, no cooling.

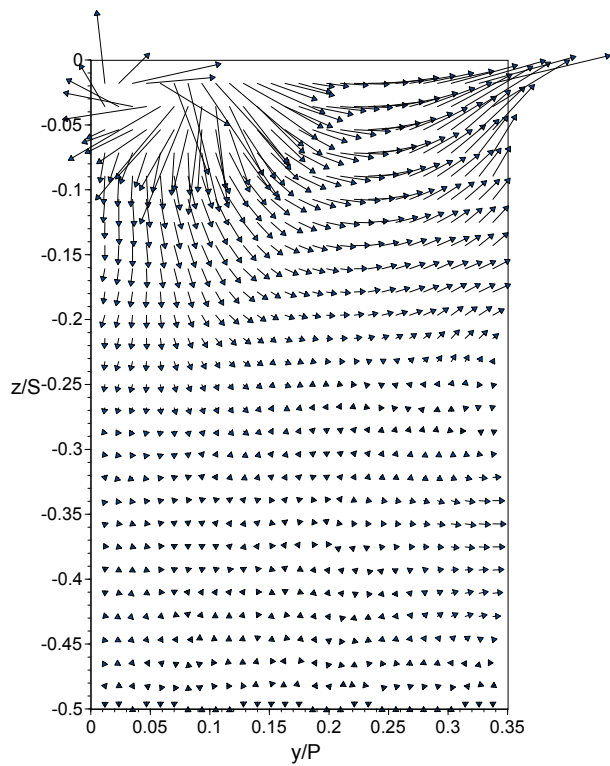


Figure C41. SS4 - Small tip gap, 0.19% dirt purge cooling.

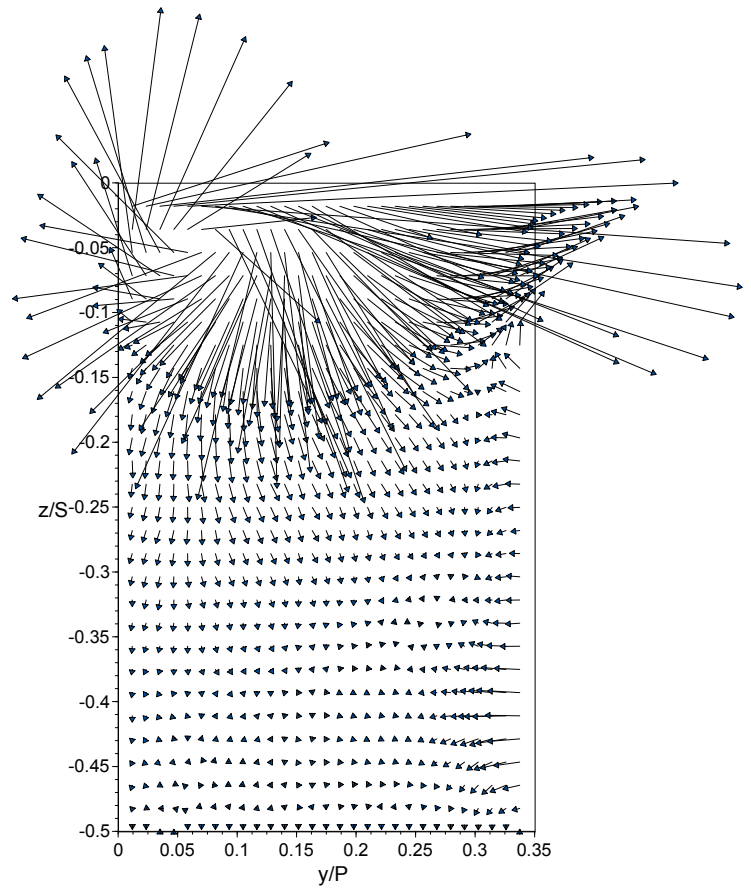


Figure C42. SS4 - Large tip gap, 0.19% dirt purge cooling.

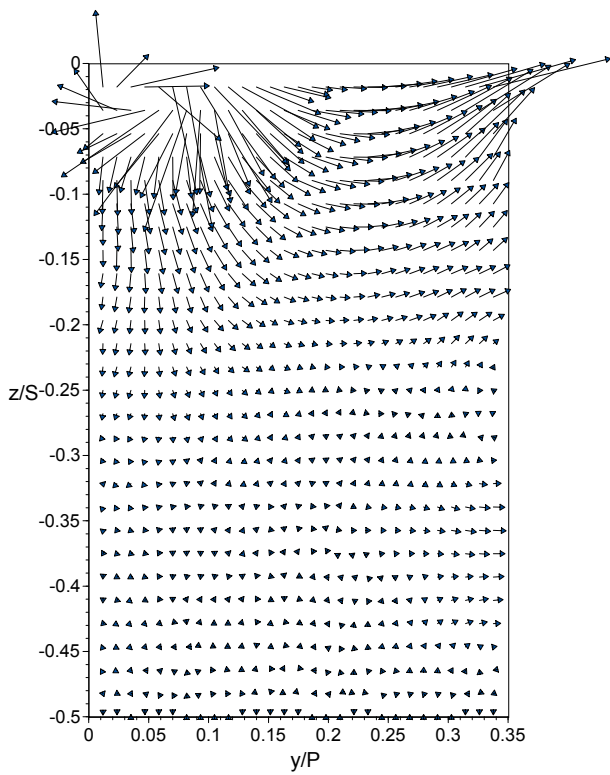


Figure C43. SS4 - Small tip gap, 0.29% dirt purge cooling.

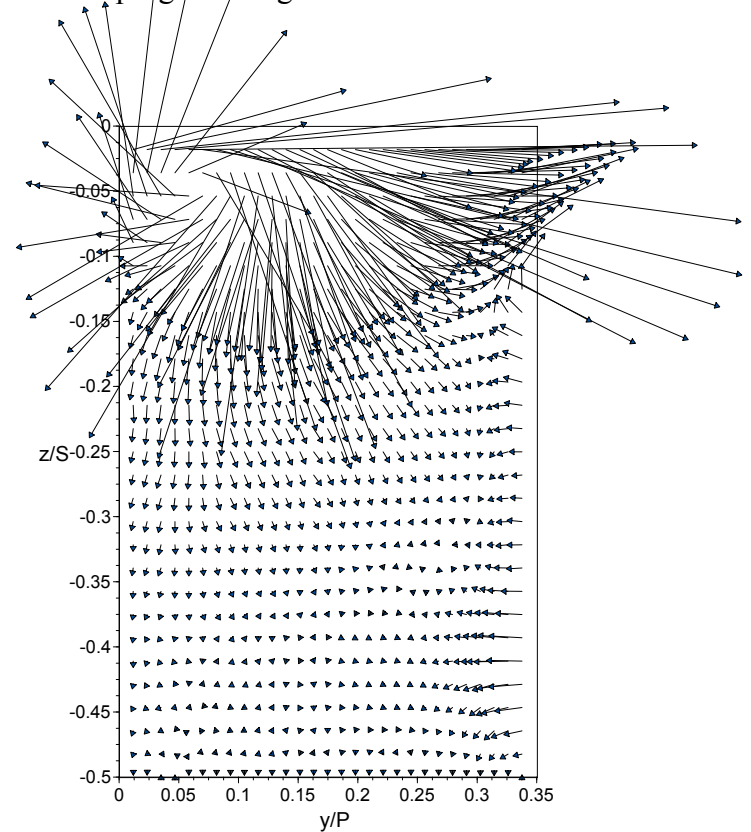


Figure C44. SS4 - Large tip gap, 0.29% dirt purge cooling.

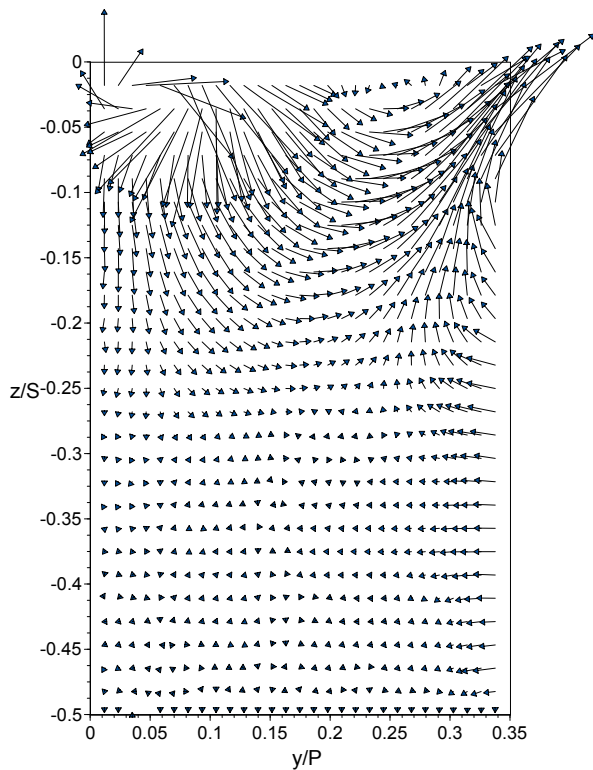


Figure C45. SS4 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

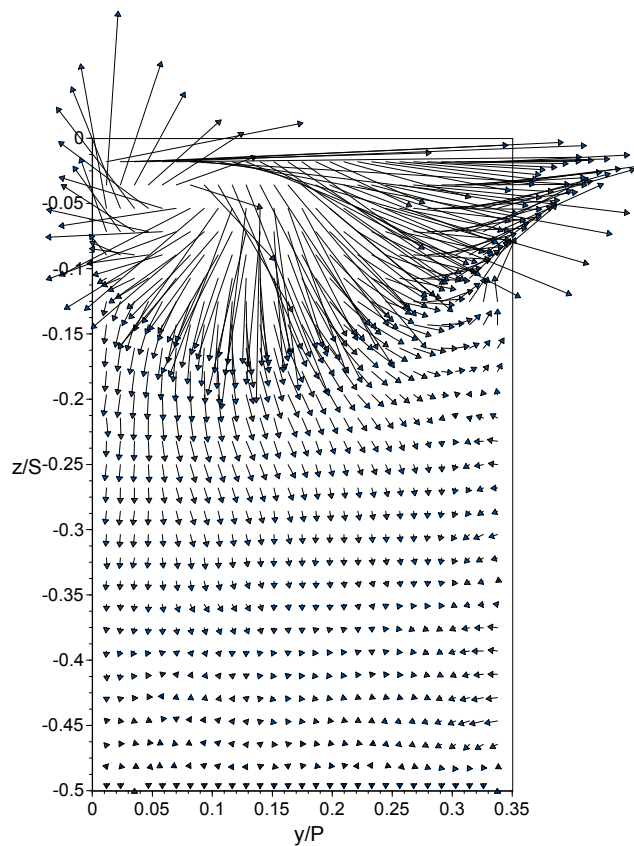


Figure C46. SS4 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

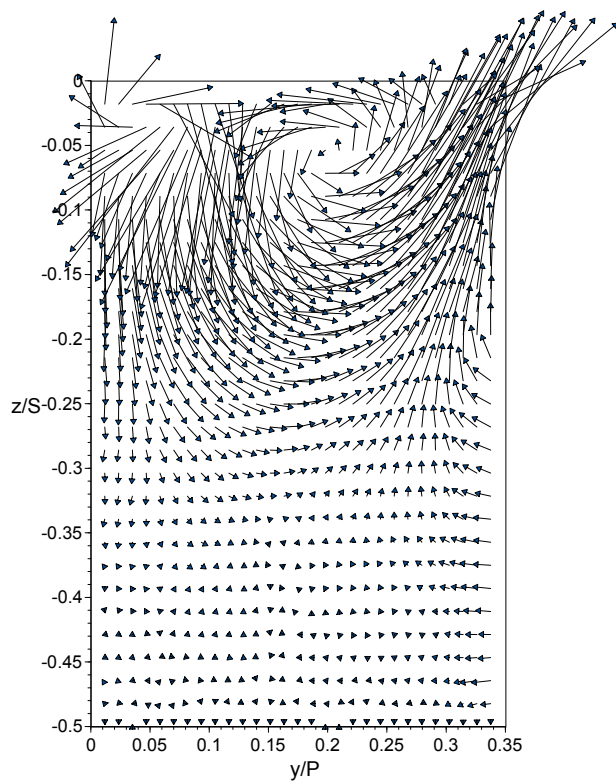


Figure C47. SS4 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

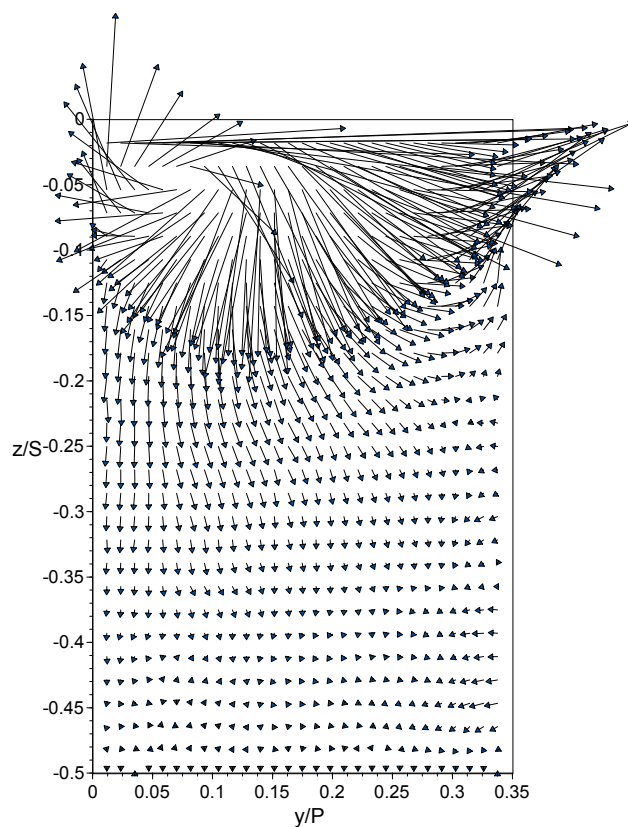


Figure C48. SS4 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

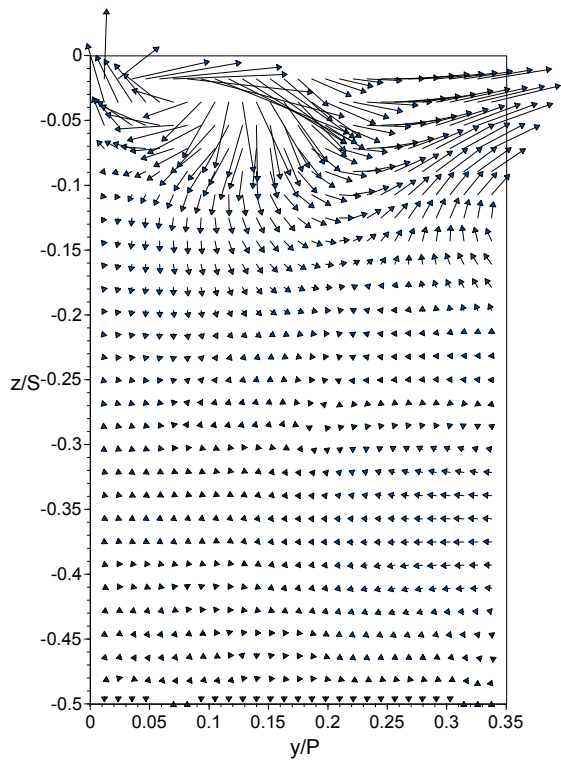


Figure C49. SS5 - Small tip gap, flat tip.

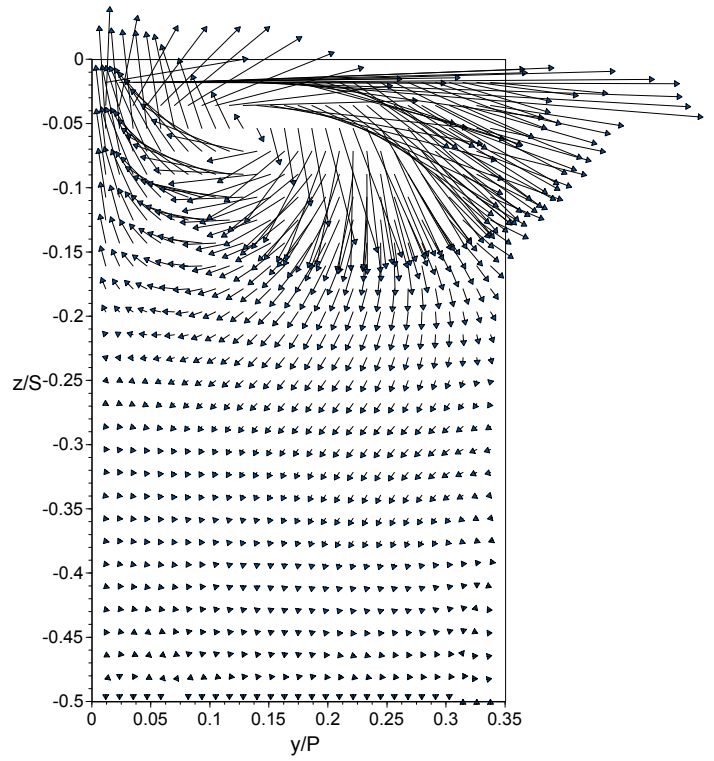


Figure C50. SS5 - Large tip gap, flat tip.

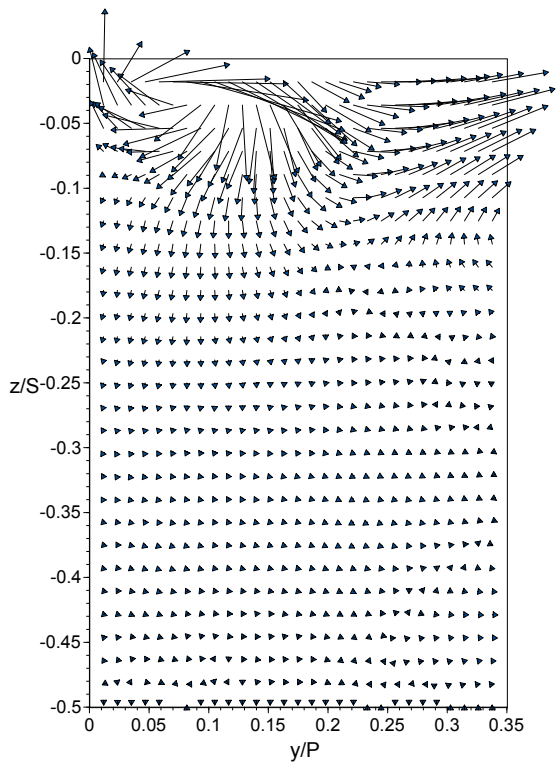


Figure C51. SS5 - Small tip gap, dirt purge cavity, no cooling.

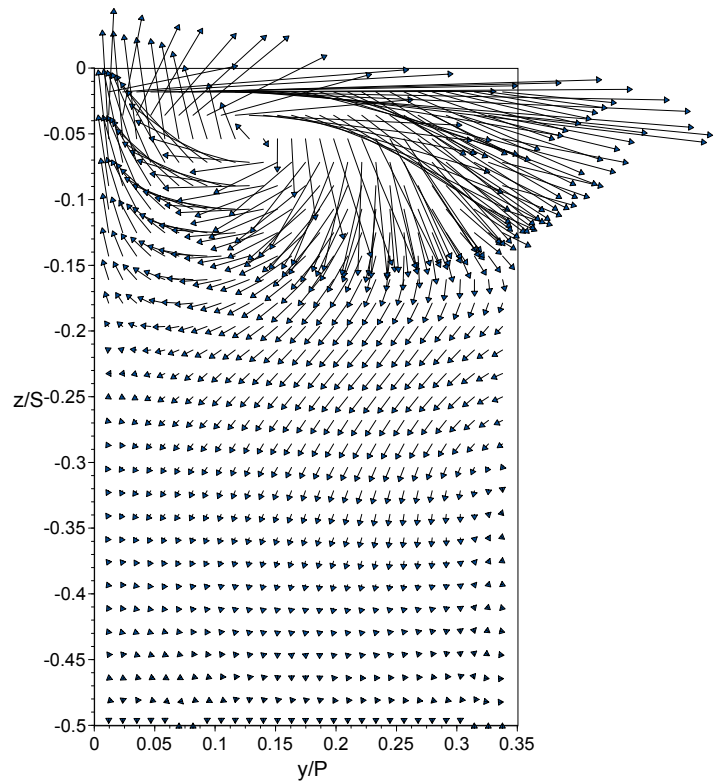


Figure C52. SS5 - Large tip gap, dirt purge cavity, no cooling.

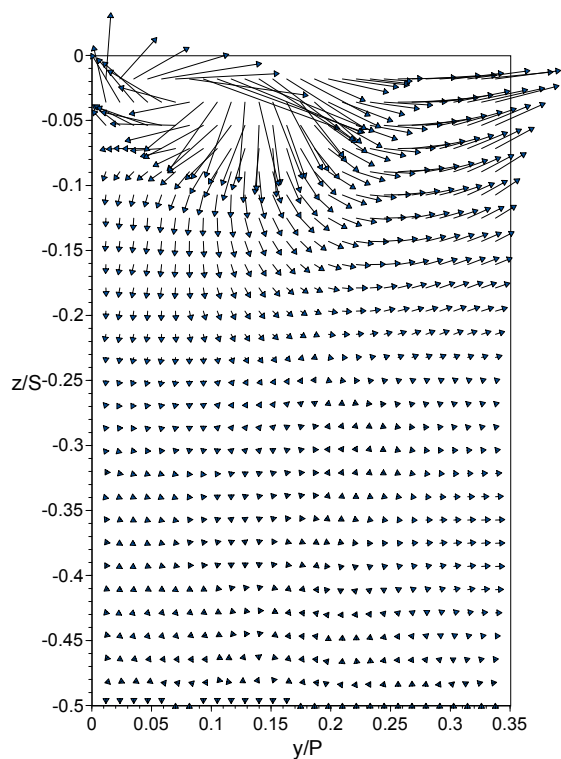


Figure C53. SS5 - Small tip gap, 0.19% dirt purge cooling.

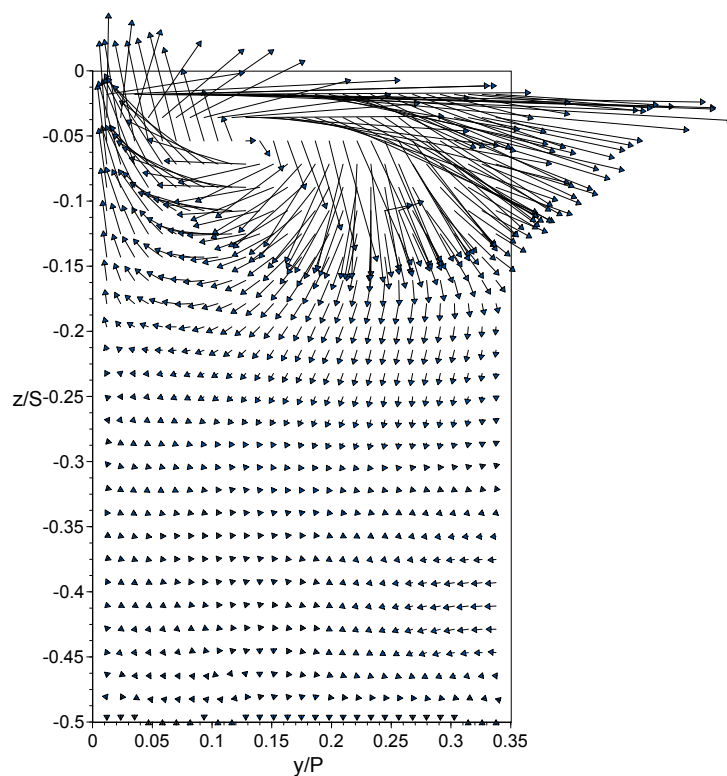


Figure C54. SS5 - Large tip gap, 0.19% dirt purge cooling.

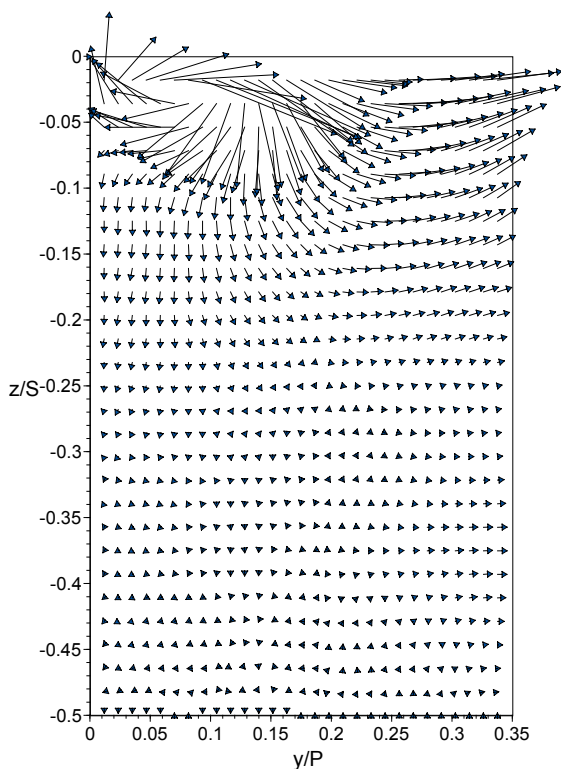


Figure C55. SS5 - Small tip gap, 0.29% dirt purge cooling.

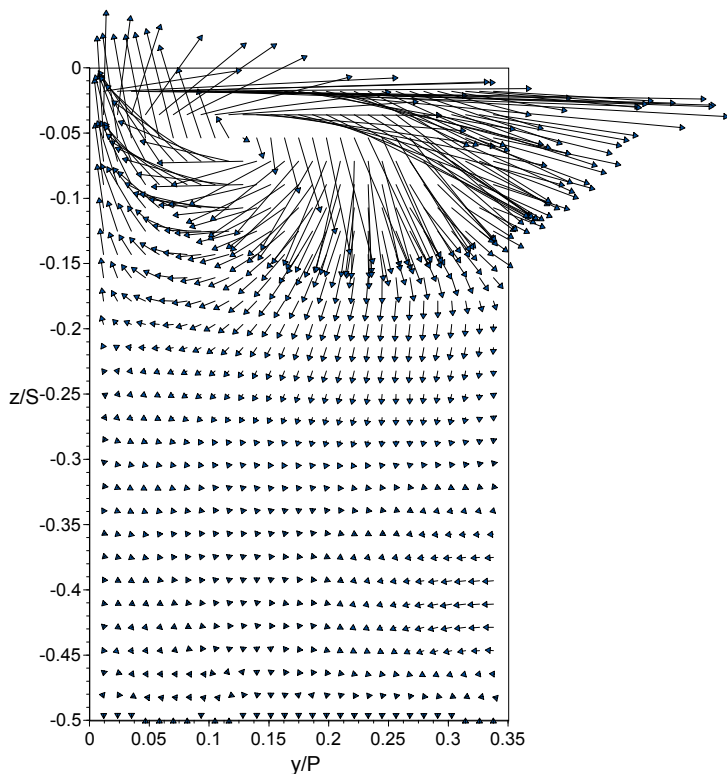


Figure C56. SS5 - Large tip gap, 0.29% dirt purge cooling.

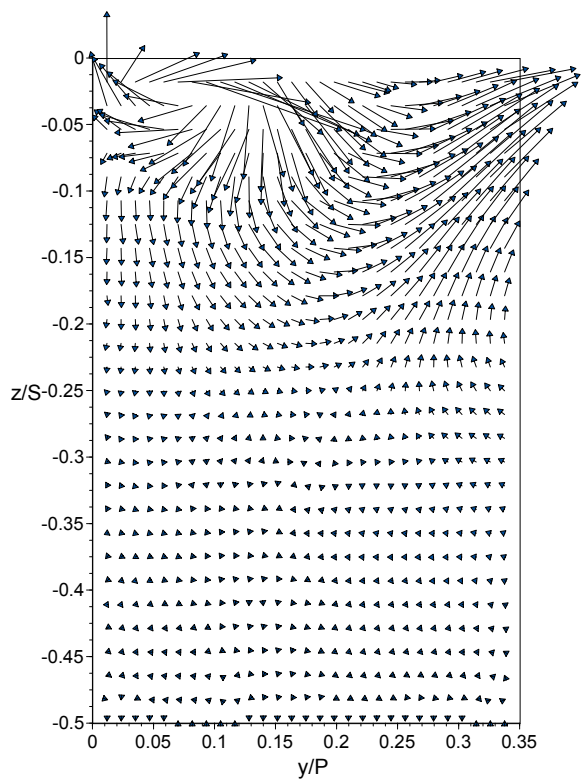


Figure C57. SS5 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

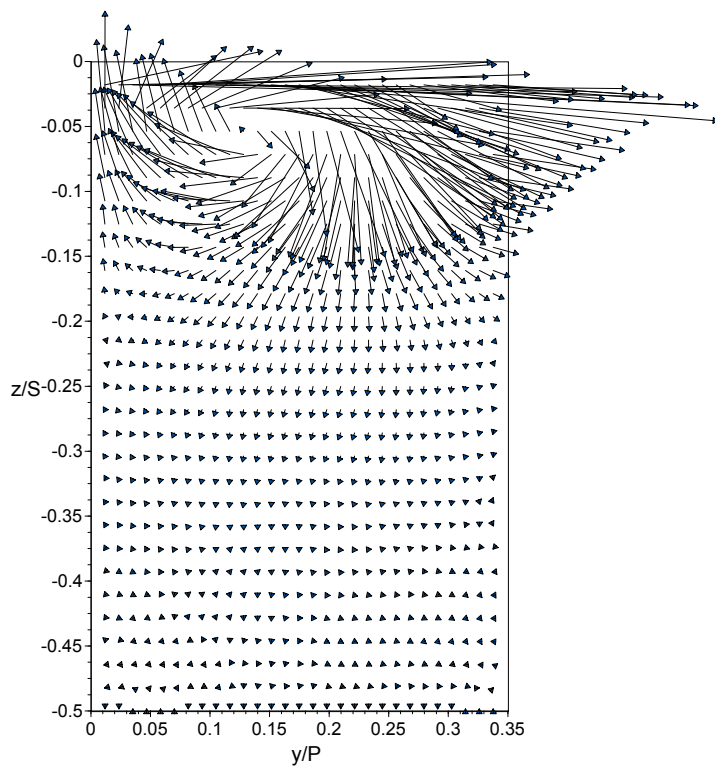


Figure C58. SS5 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

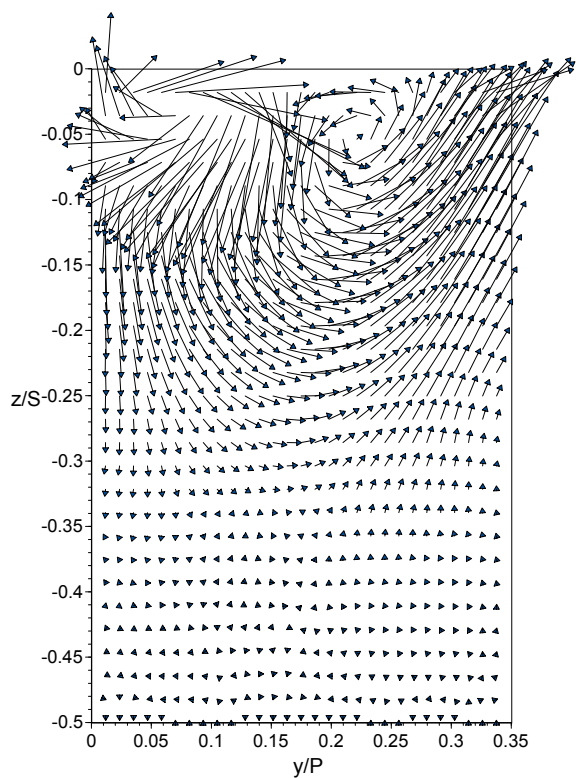


Figure C59. SS5 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

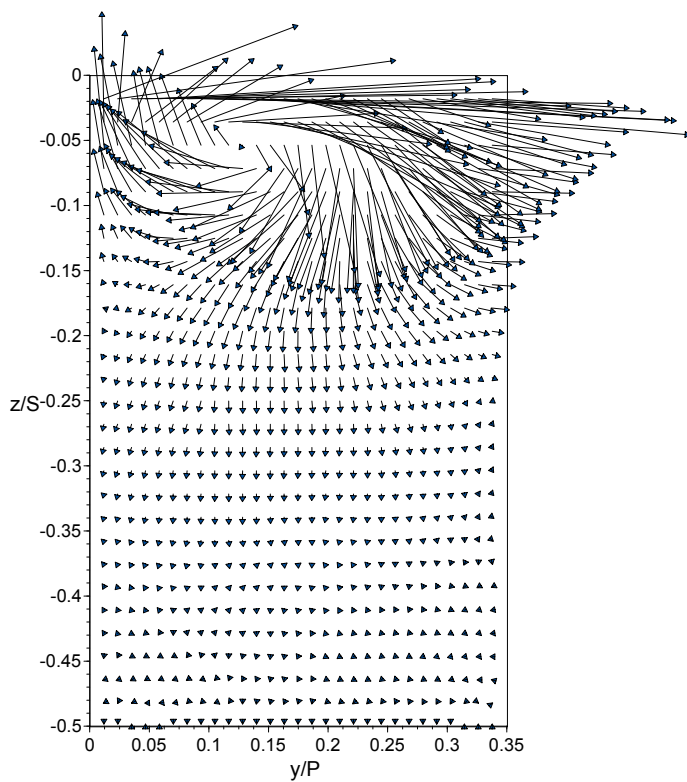


Figure C60. SS5 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

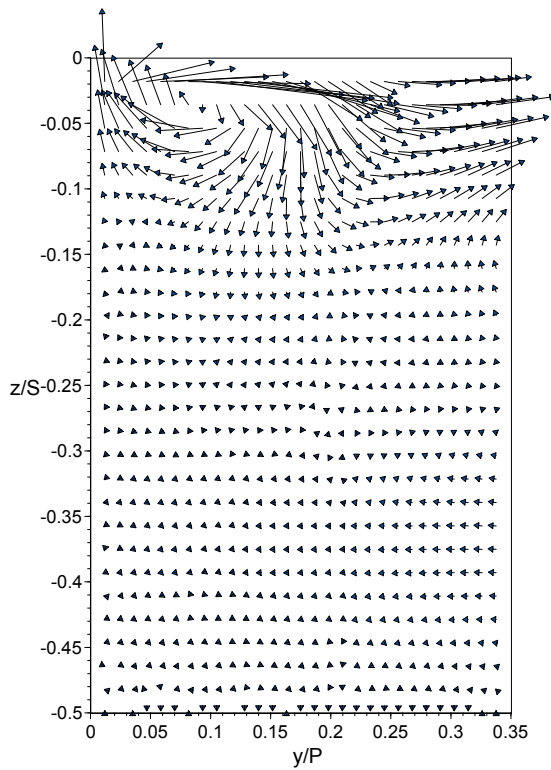


Figure C61. SS6 Small tip gap, flat tip.

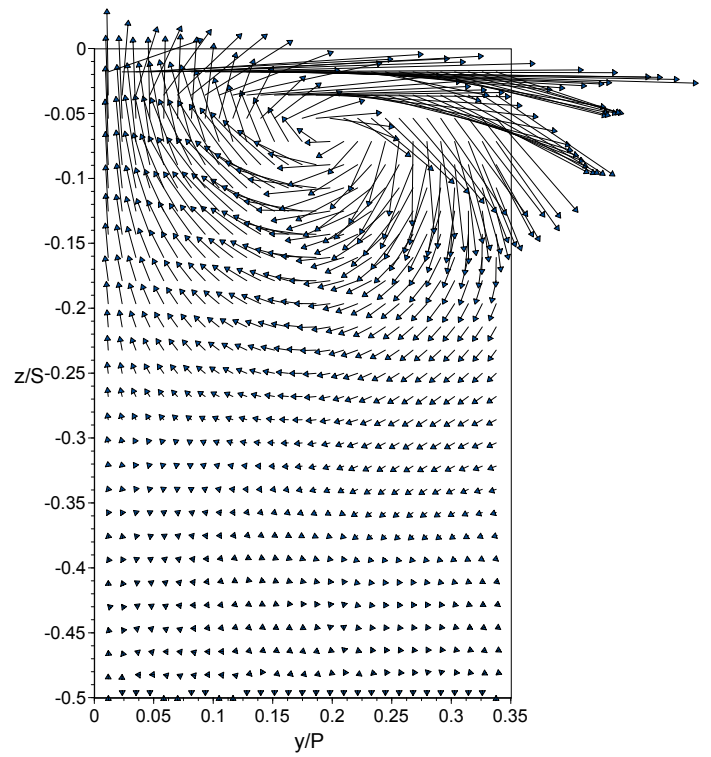


Figure C62. SS6 - Large tip gap, flat tip.

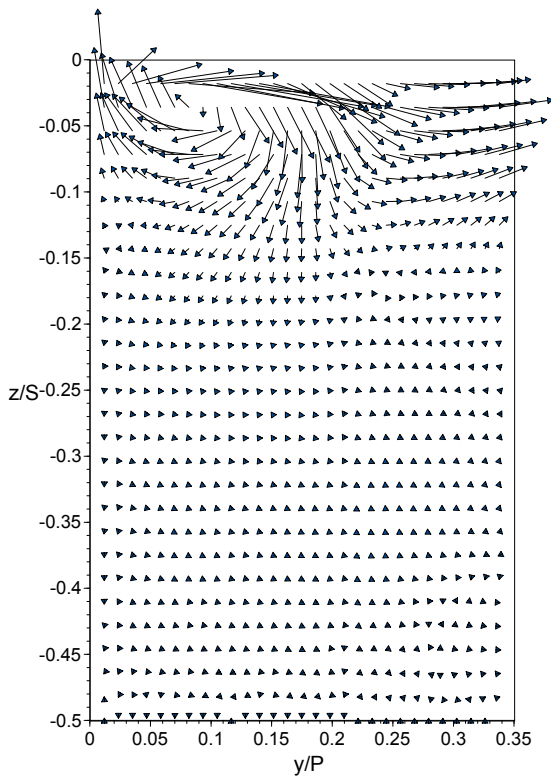


Figure C63. SS6 - Small tip gap, dirt purge cavity, no cooling.

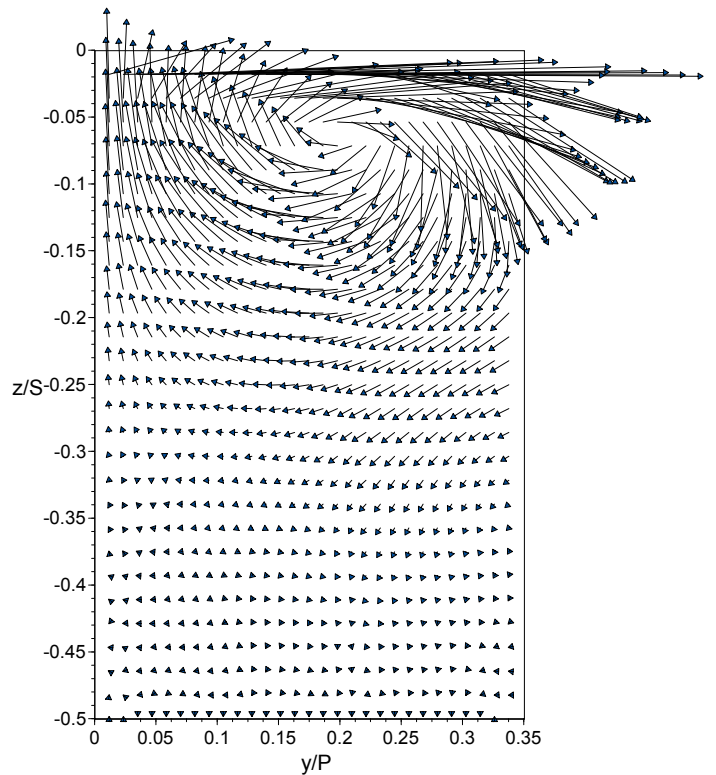


Figure C64. SS6 - Large tip gap, dirt purge cavity, no cooling.

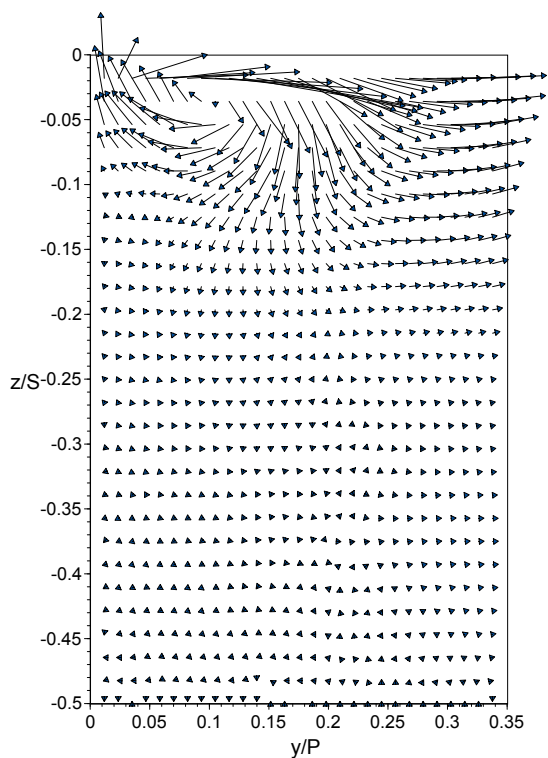


Figure C65. SS6 - Small tip gap, 0.19% dirt purge cooling.

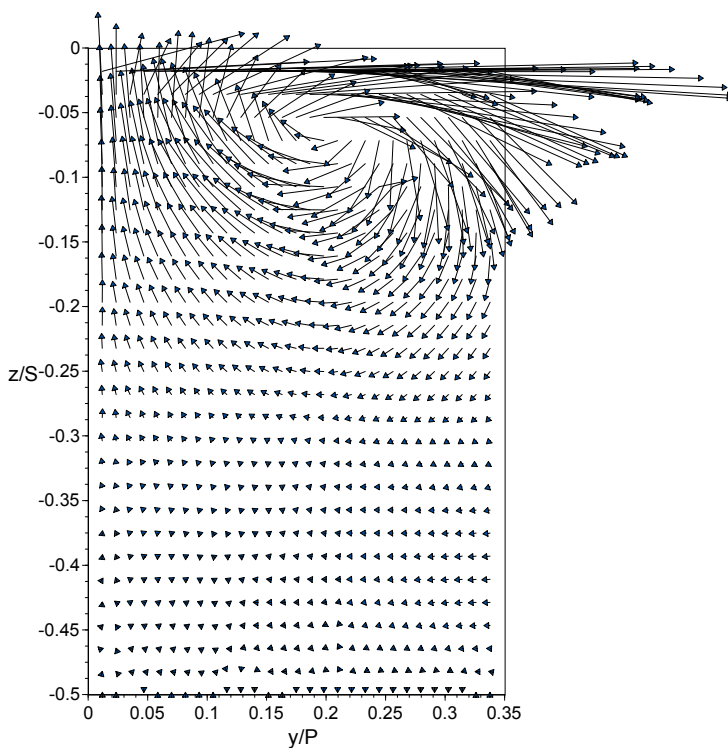


Figure C66. SS6 - Large tip gap, 0.19% dirt purge cooling.

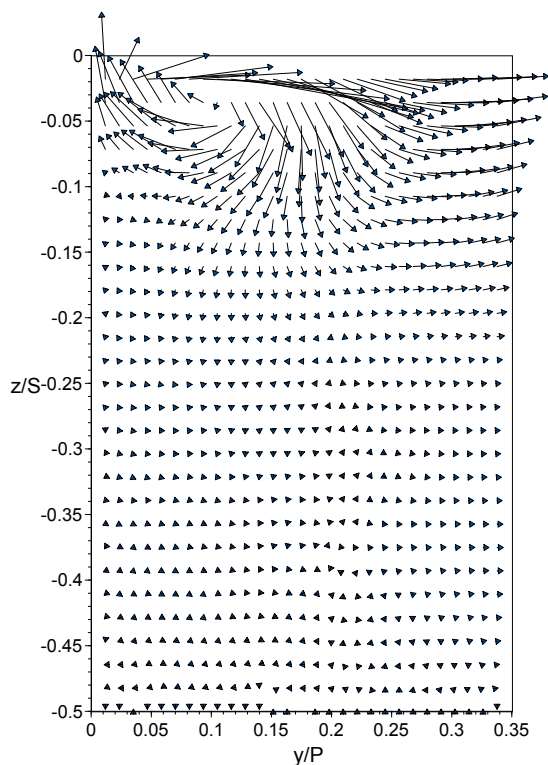
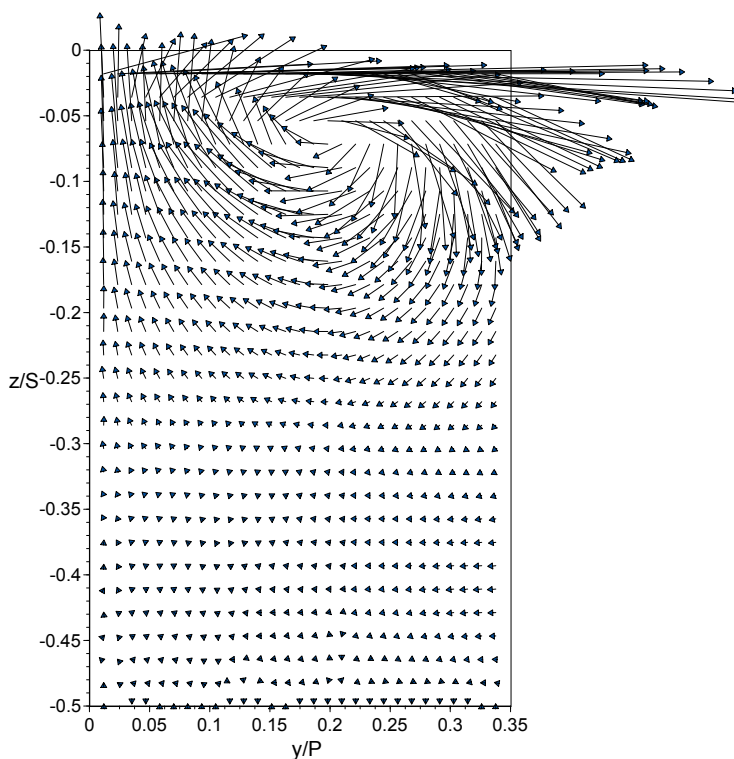


Figure C67. SS6 Small tip gap, 0.29% dirt purge cooling.



FigureCA68. SS6 - Large tip gap, 0.29% dirt purge cooling.

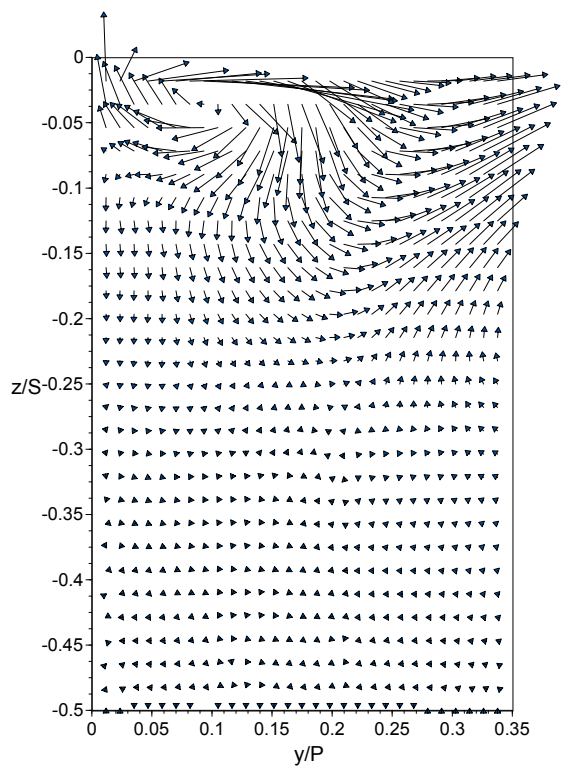


Figure C69. SS6 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

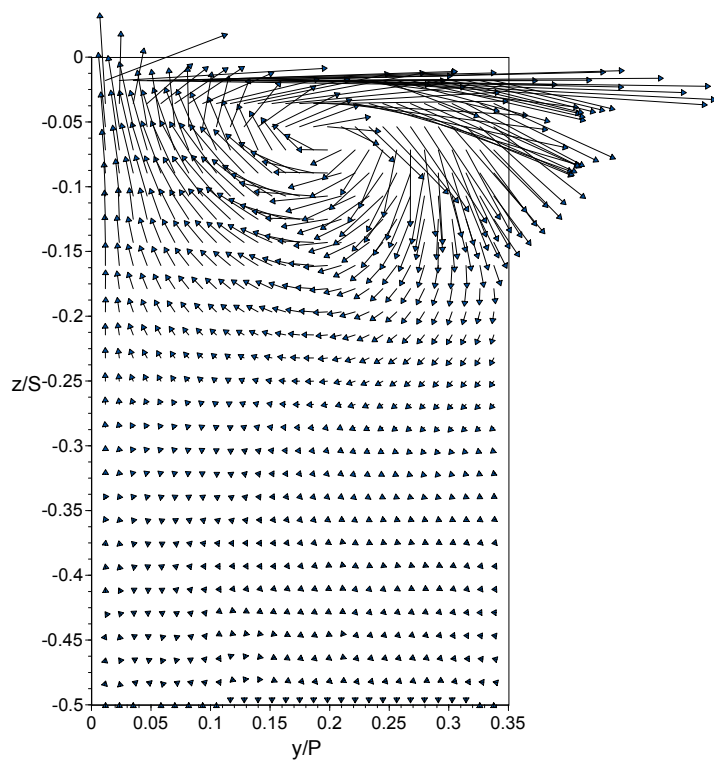


Figure C70. SS6 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

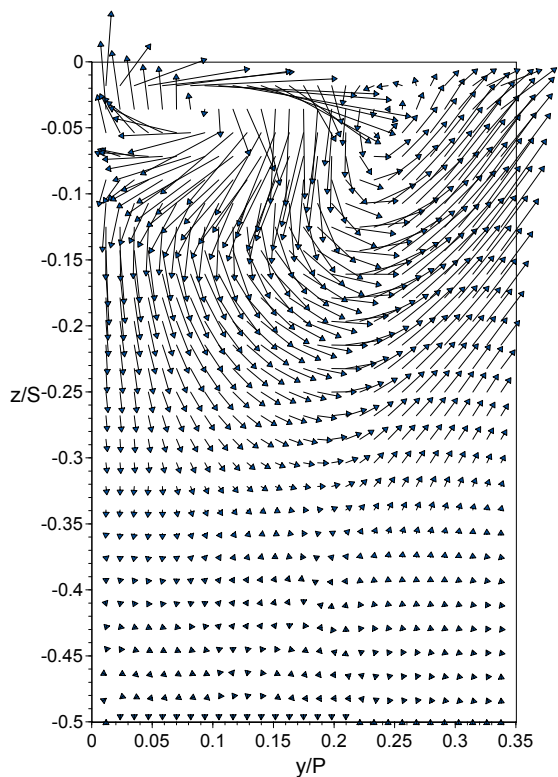


Figure C71. SS6 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

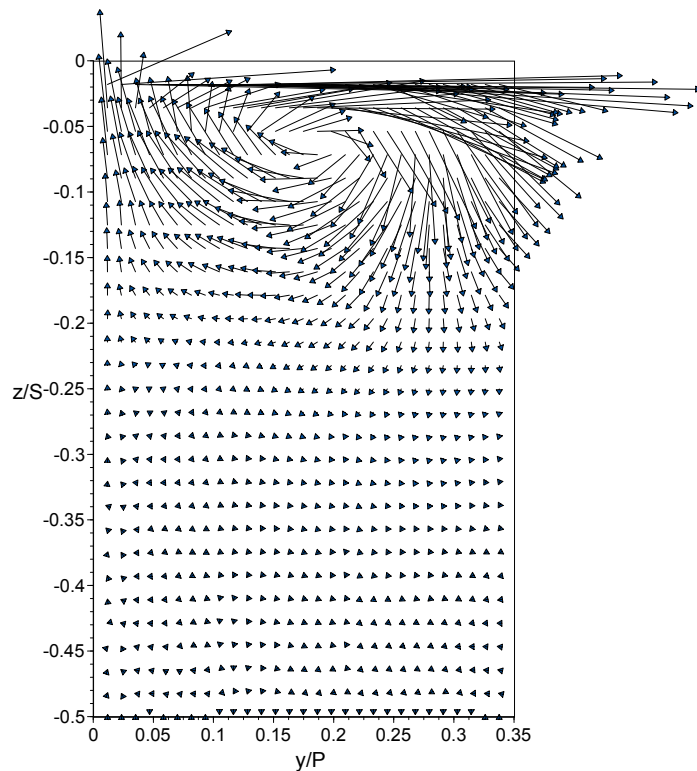


Figure C72. SS6 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

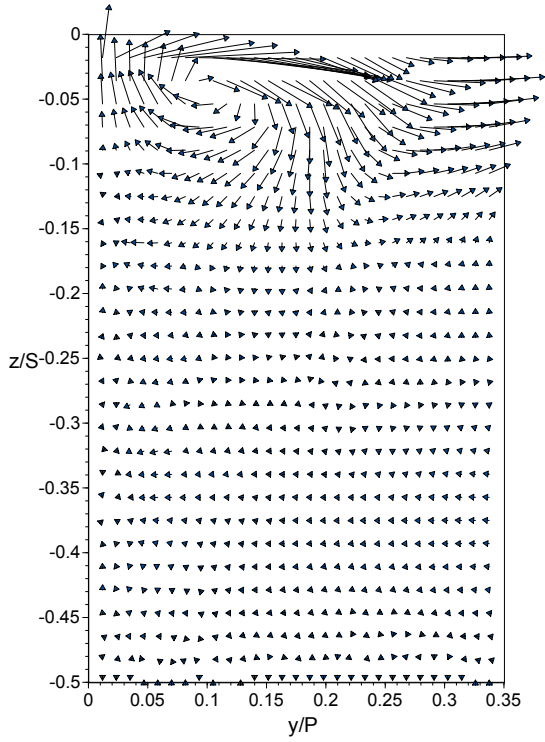


Figure C73. SS7 - Small tip gap, flat tip.

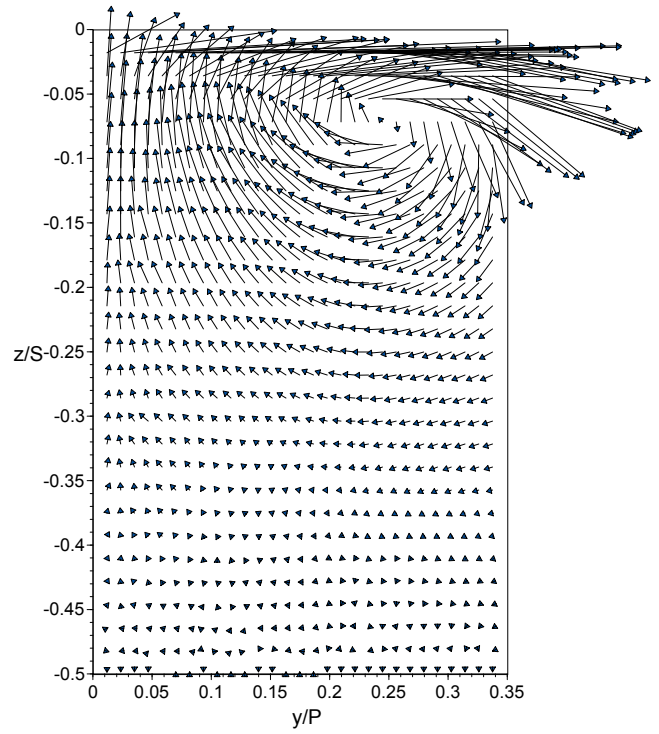


Figure C74. SS7 - Large tip gap, flat tip.

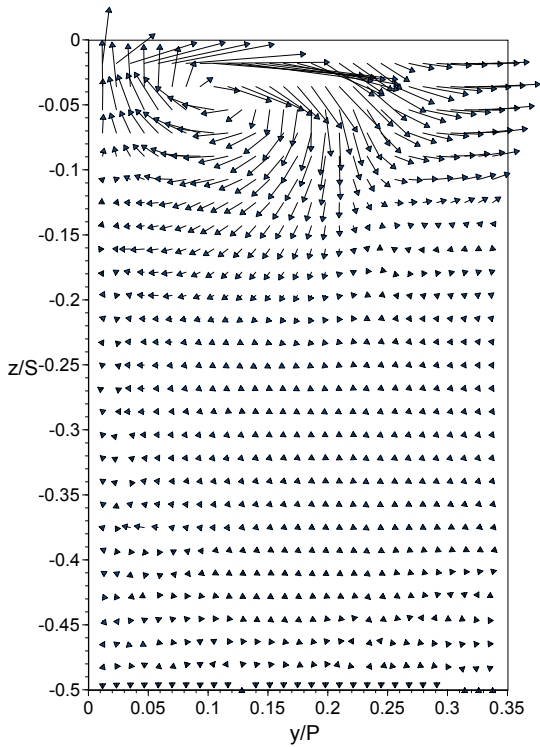


Figure C75. SS7 - Small tip gap, dirt purge cavity, no cooling.

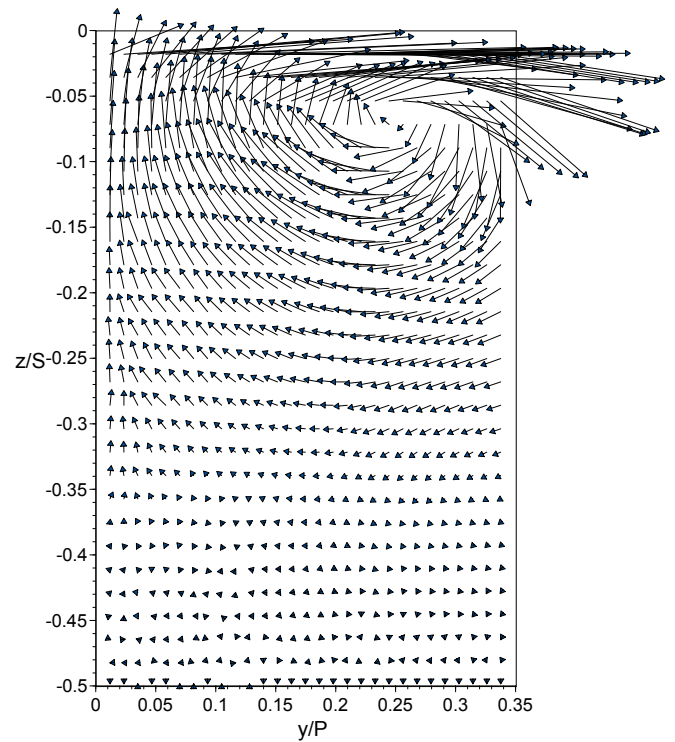


Figure C76. SS7 - Large tip gap, dirt purge cavity, no cooling.

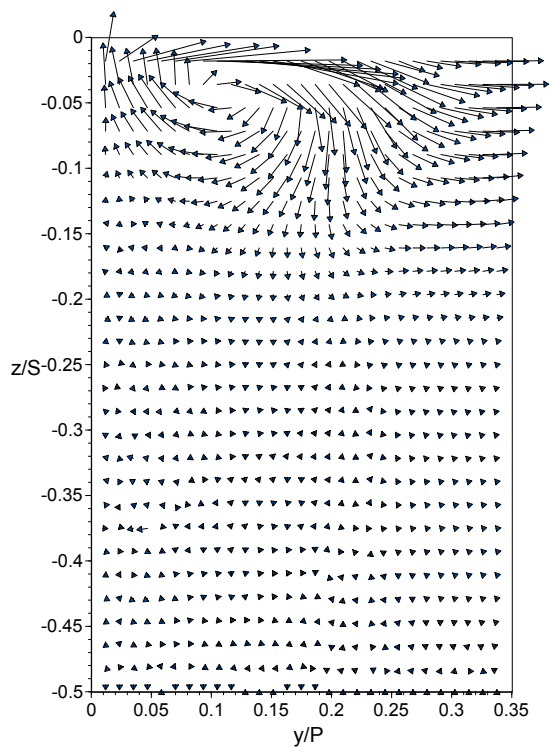


Figure C77. SS7 - Small tip gap, 0.19% dirt purge cooling.

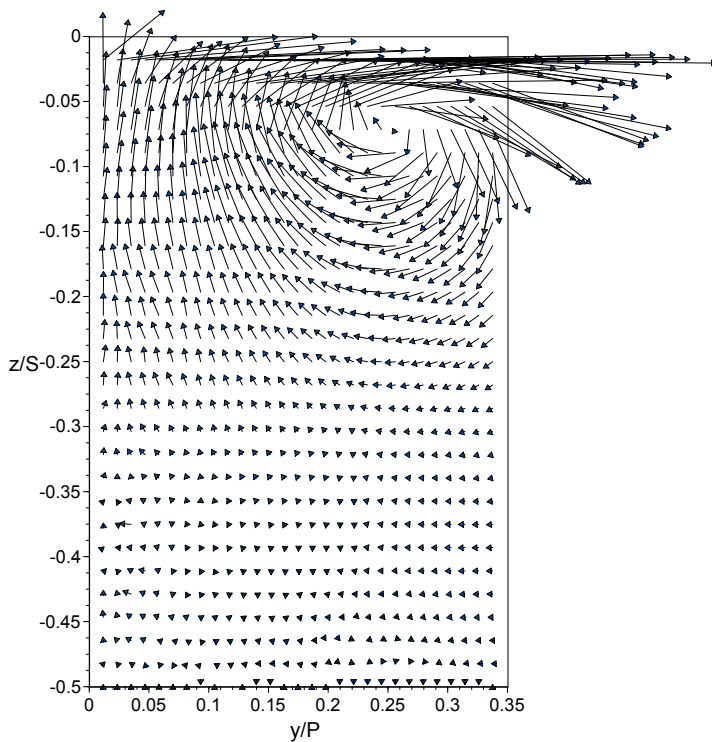


Figure C78. SS7 - Large tip gap, 0.19% dirt purge cooling.

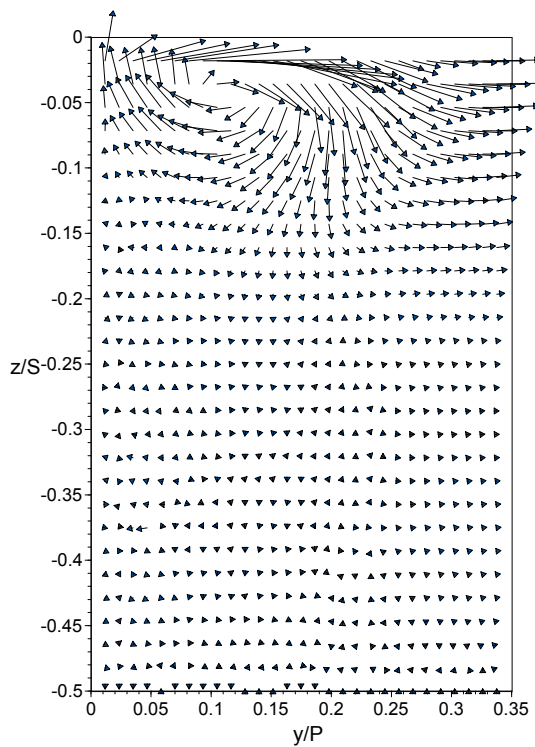


Figure C79. SS7 - Small tip gap, 0.29% dirt purge cooling.

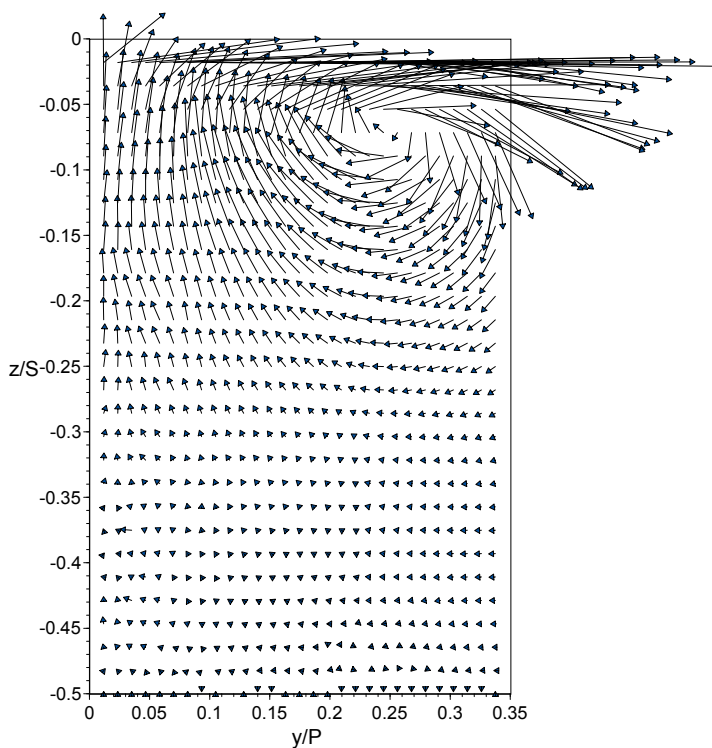


Figure C80. SS7 - Large tip gap, 0.29% dirt purge cooling.

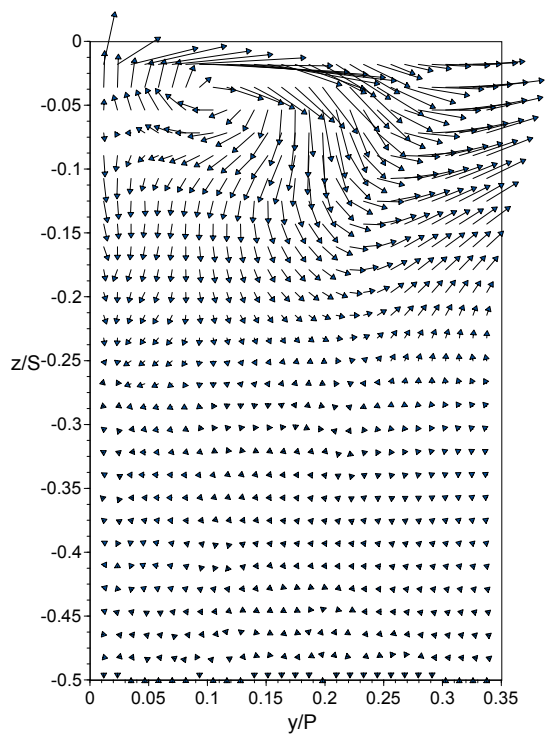


Figure C81. SS7 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

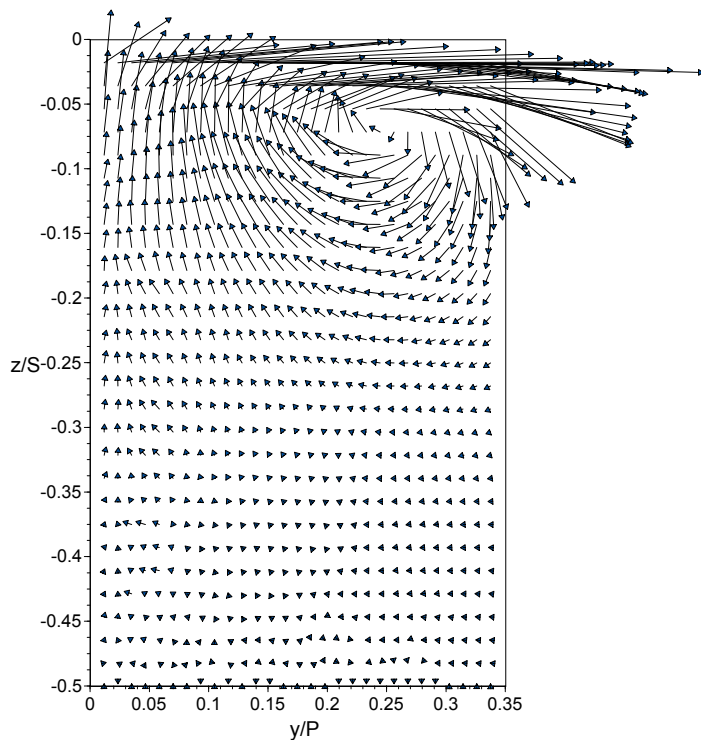


Figure C82. SS7 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

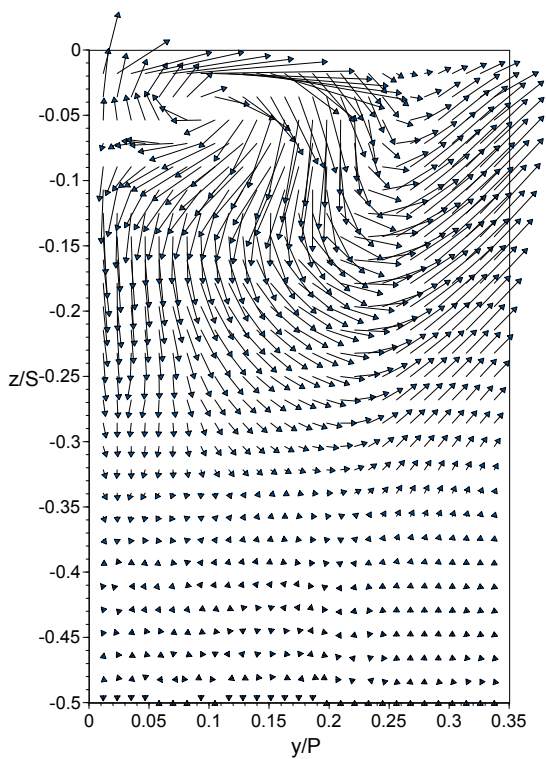


Figure C83. SS7 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

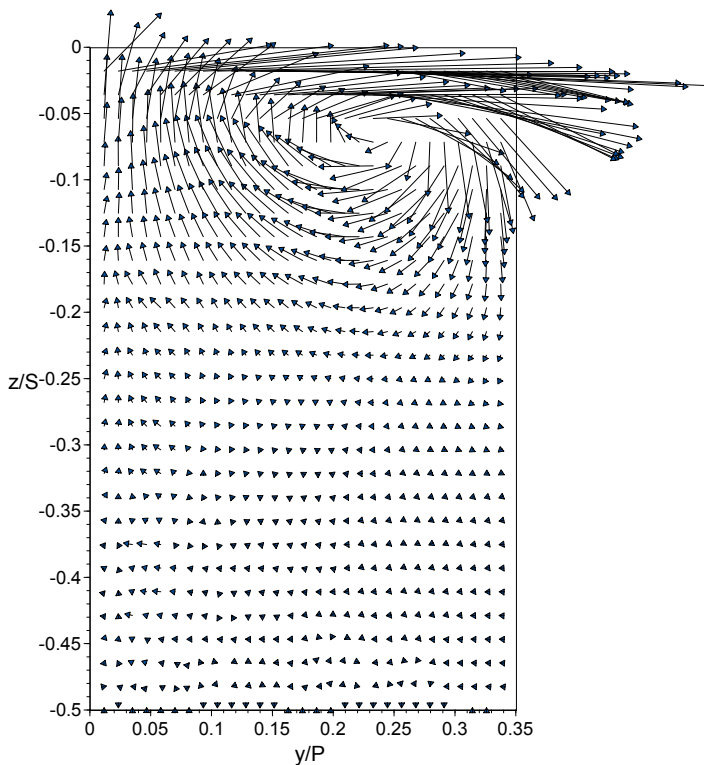


Figure C84. SS7 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

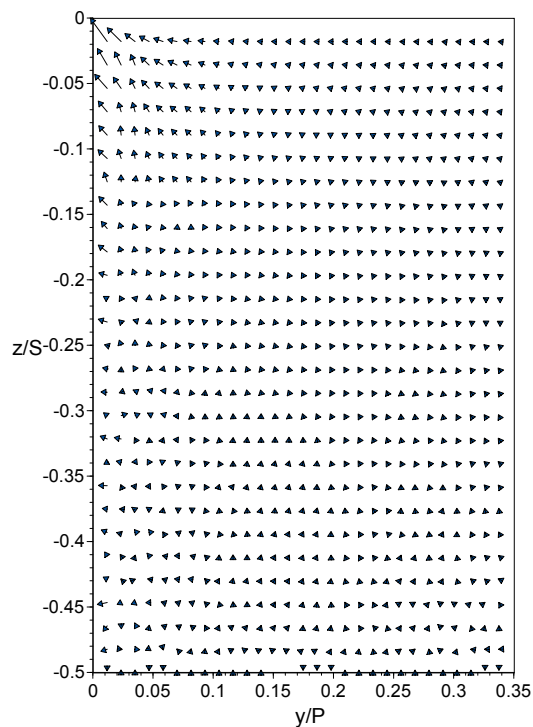


Figure C85. PS1- Small tip gap, flat tip.

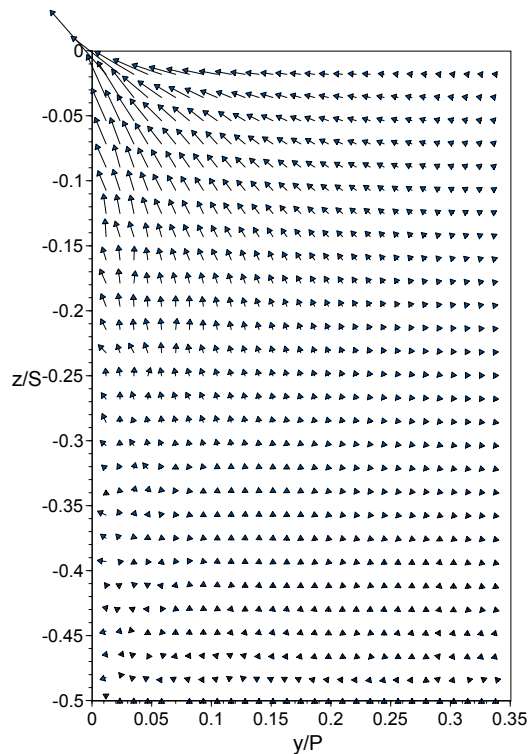


Figure C86. PS1 - Large tip gap, flat tip.

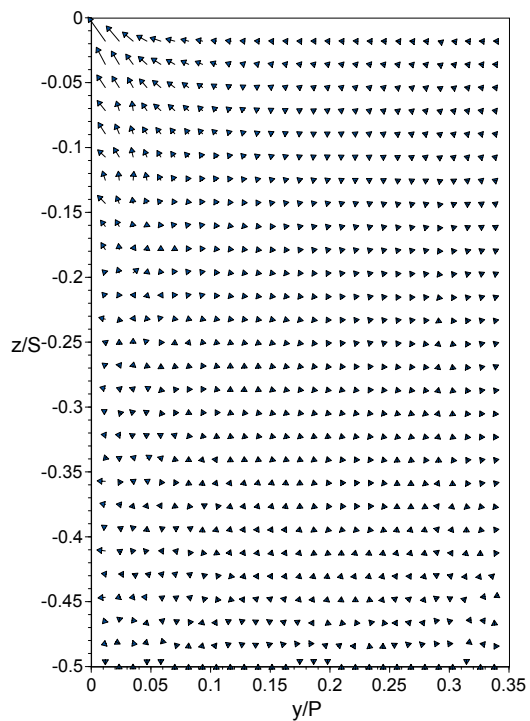


Figure C87. PS1 - Small tip gap, dirt purge cavity, no cooling.

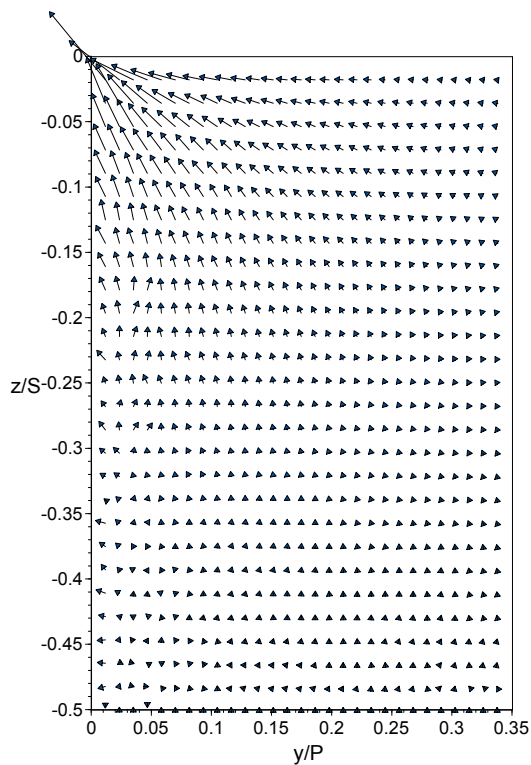


Figure C88. PS1 - Large tip gap, dirt purge cavity, no cooling.

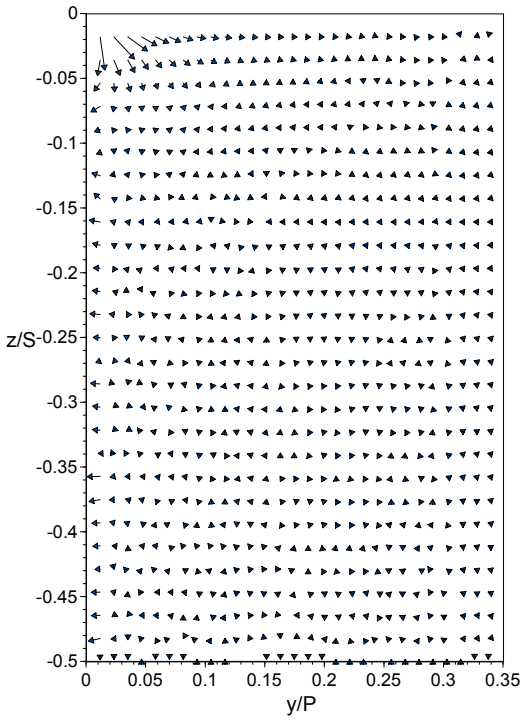


Figure C89. PS1 - Small tip gap, 0.19% dirt purge cooling.

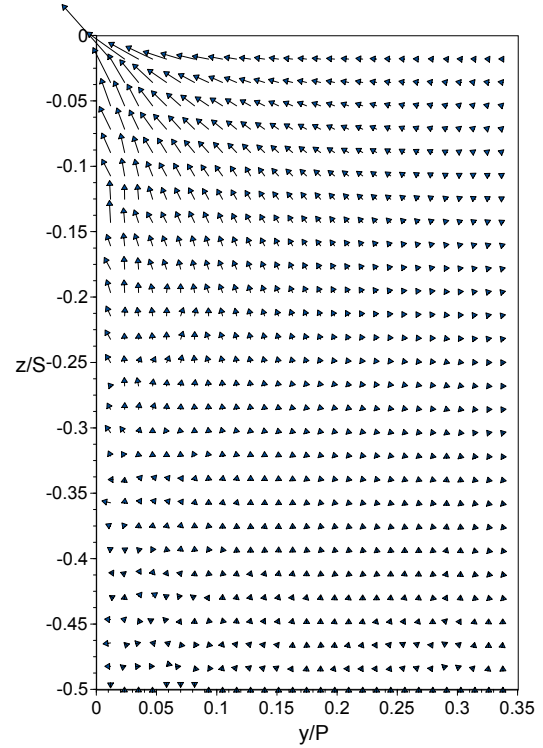


Figure C90. PS1 - Large tip gap, 0.19% dirt purge cooling.

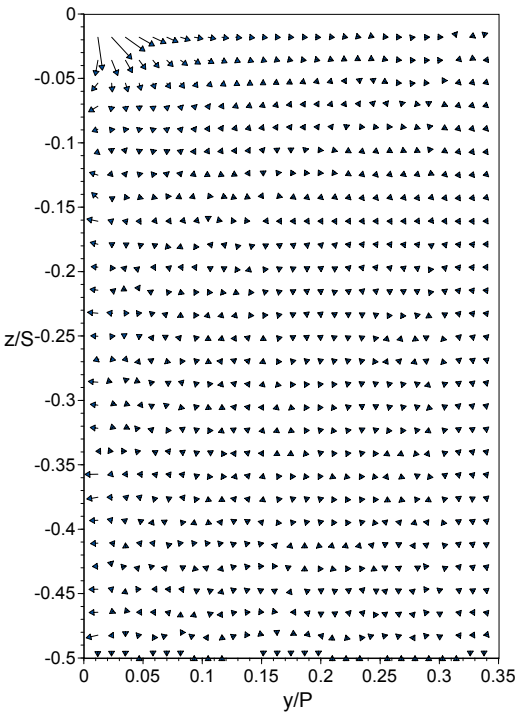


Figure C91. PS1 Small tip gap, 0.29% dirt purge cooling.

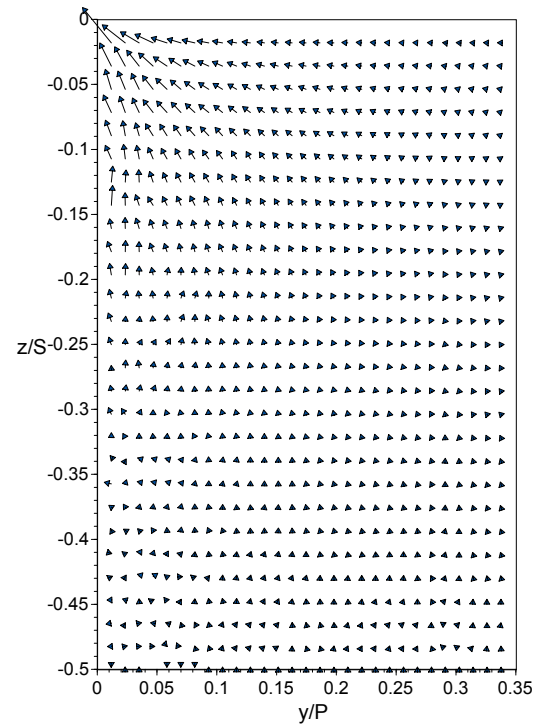


Figure C92. PS1 - Large tip gap, 0.29% dirt purge cooling.

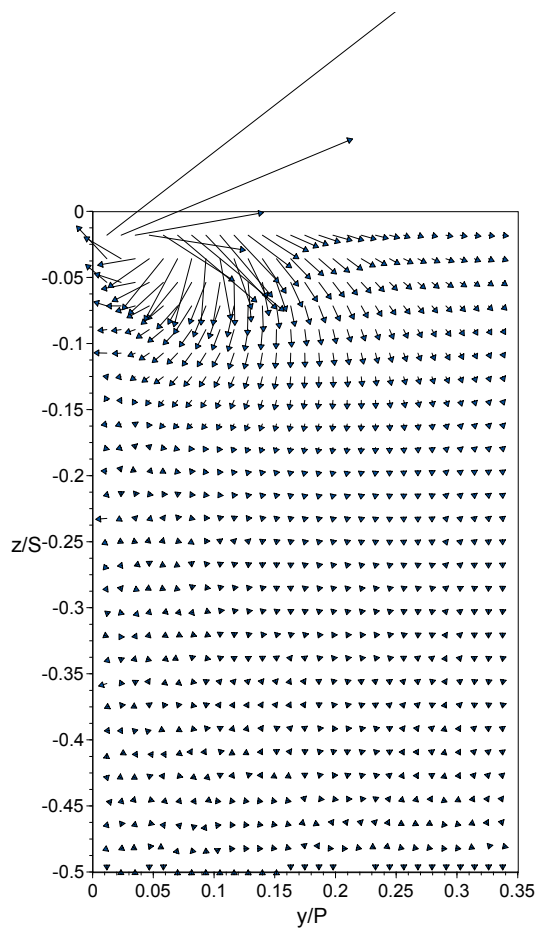


Figure C93. PS1 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

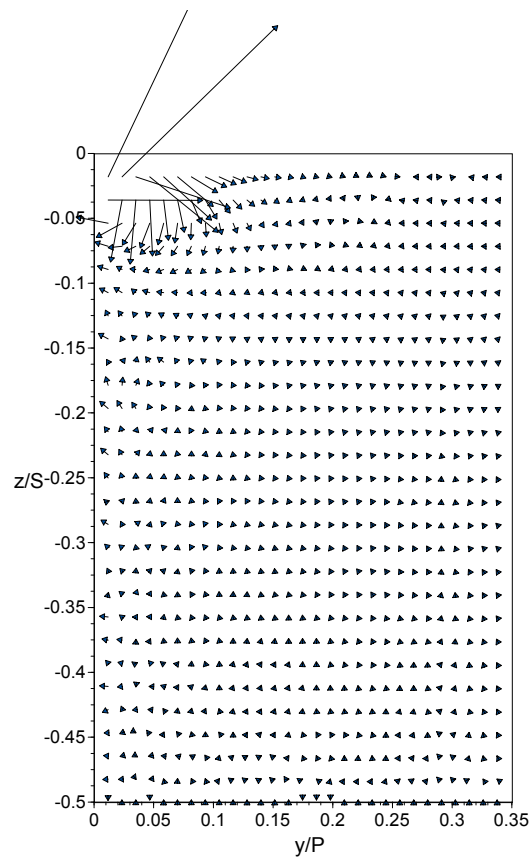


Figure C94. PS1 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

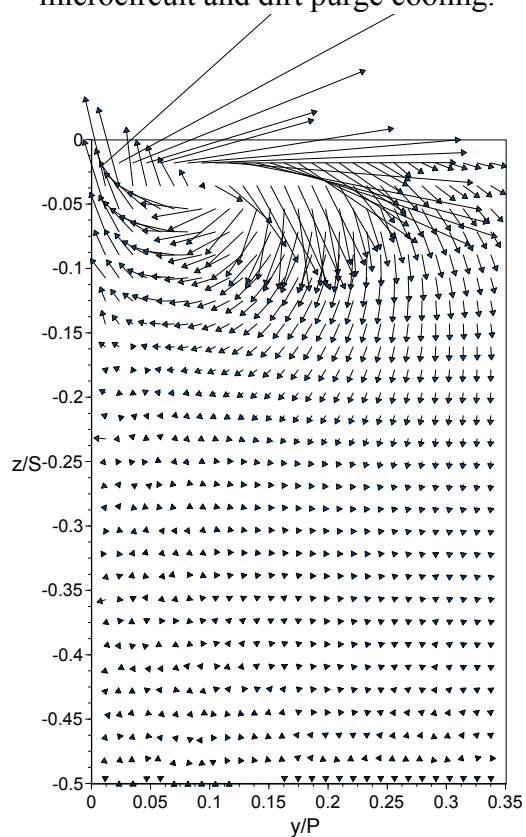


Figure C95. PS1 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

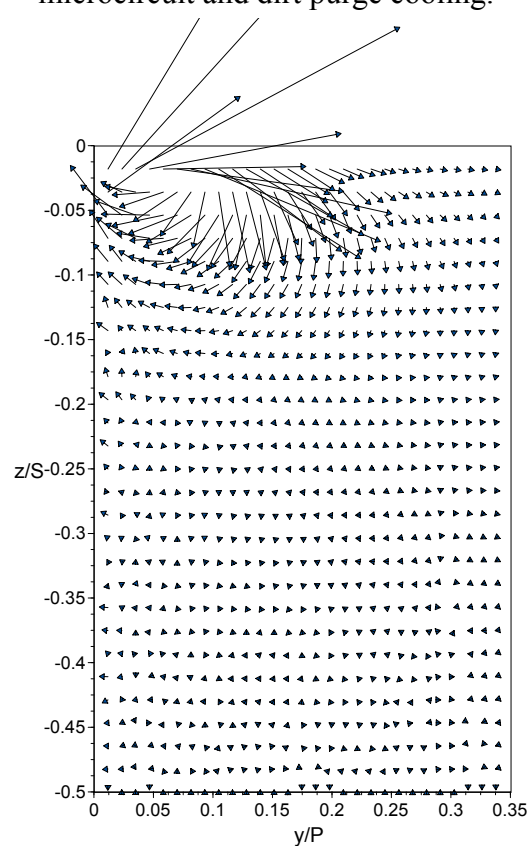


Figure C96. PS1 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

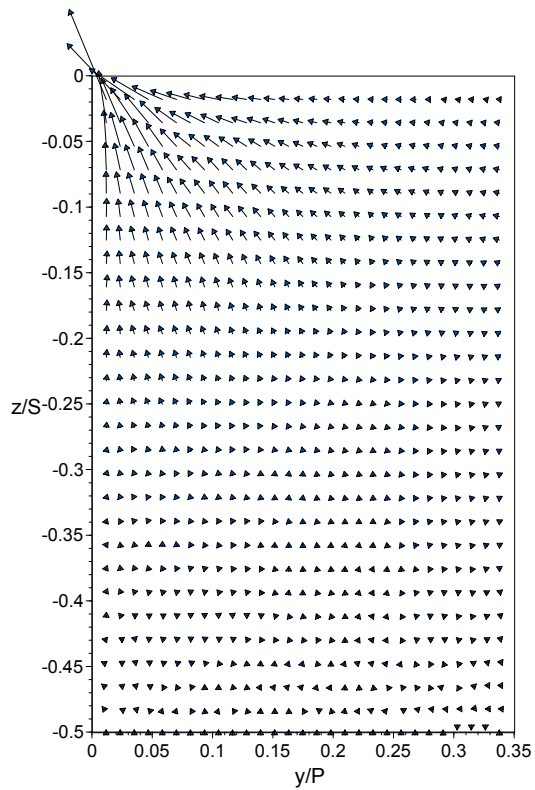


Figure C97. PS2 - Small tip gap, flat tip.

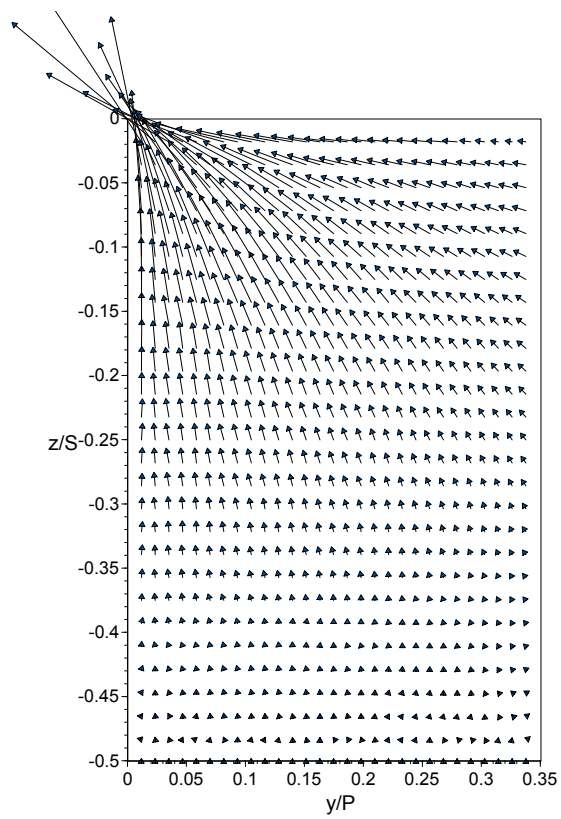


Figure C98. PS2 - Large tip gap, flat tip.

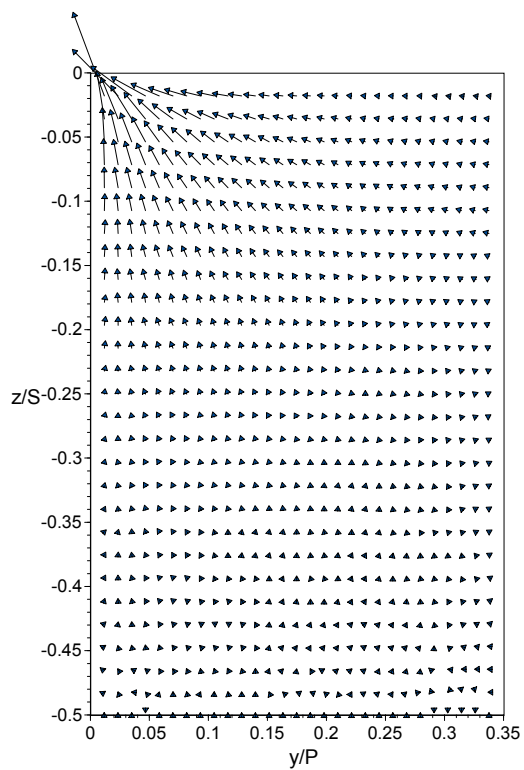


Figure C99. PS2 - Small tip gap, dirt purge cavity, no cooling.

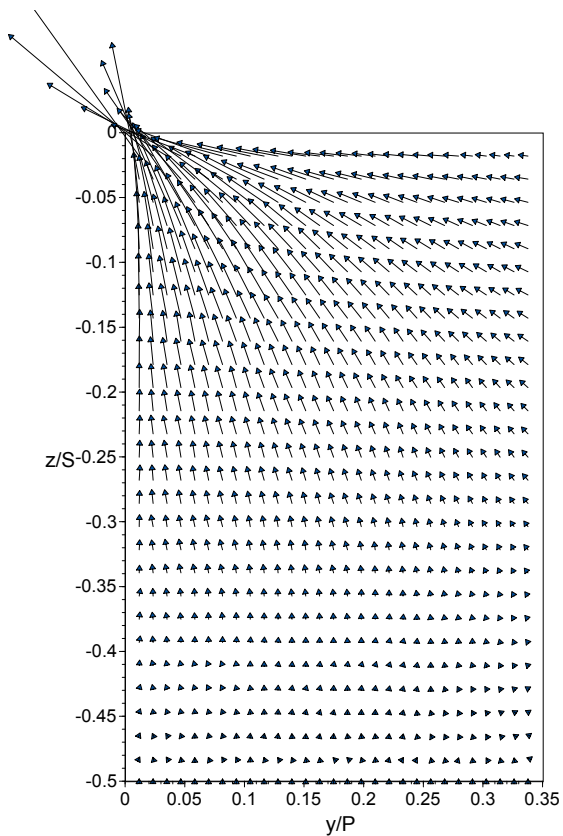


Figure C100. PS2 - Large tip gap, dirt purge cavity, no cooling.

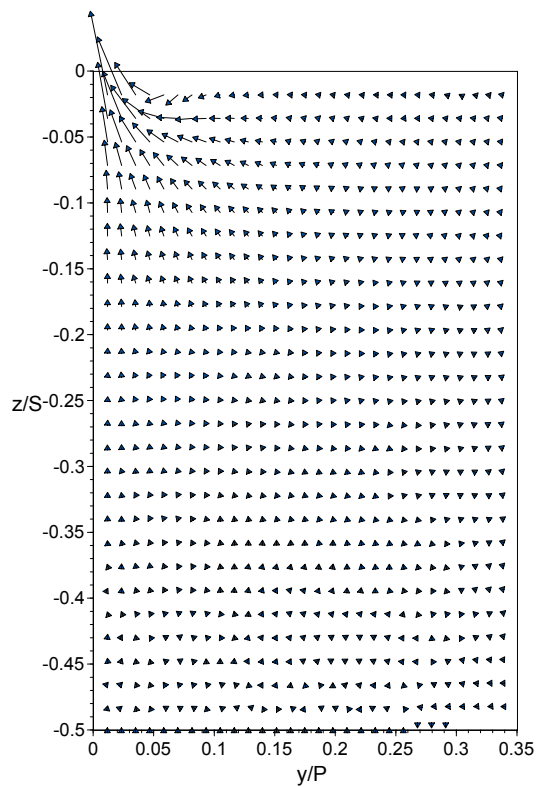


Figure C101. PS2 - Small tip gap, 0.19% dirt purge cooling.

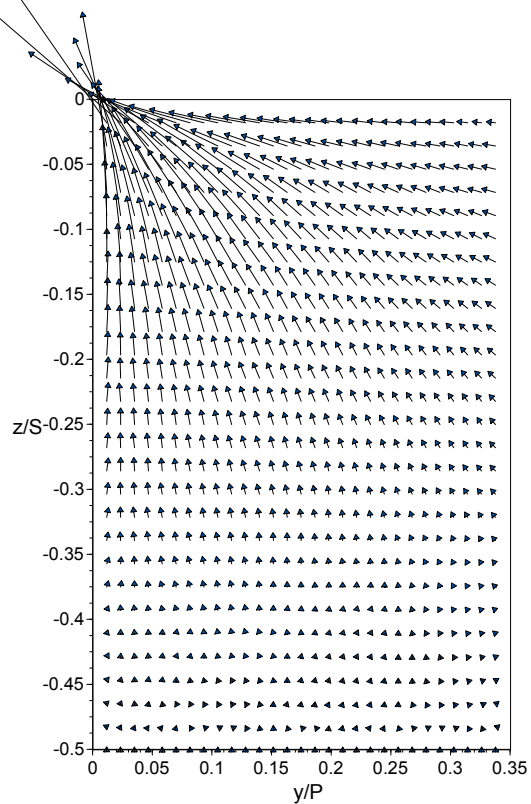


Figure C102. PS2 - Large tip gap, 0.19% dirt purge cooling.

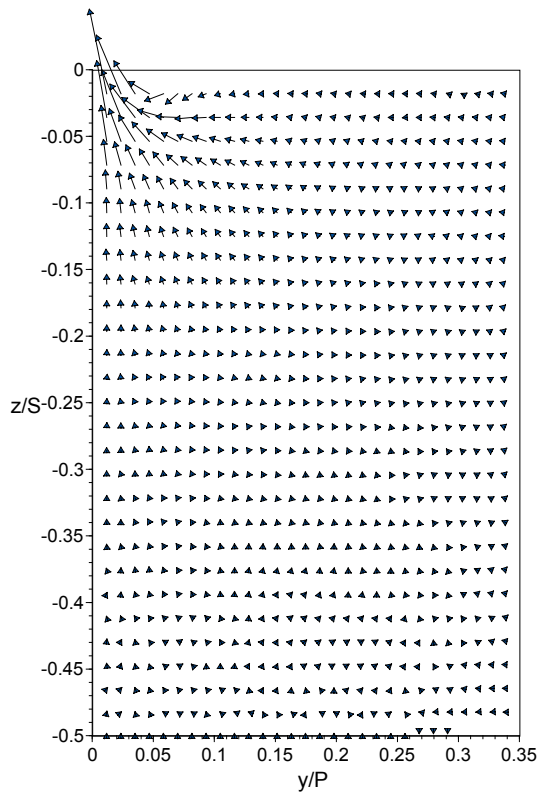


Figure C103. PS2 - Small tip gap, 0.29% dirt purge cooling.

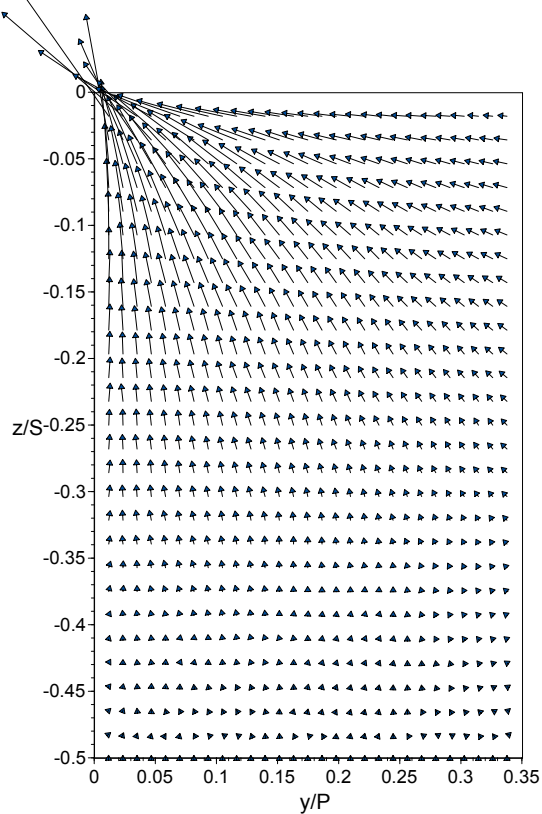


Figure C104. PS2 - Large tip gap, 0.29% dirt purge cooling.

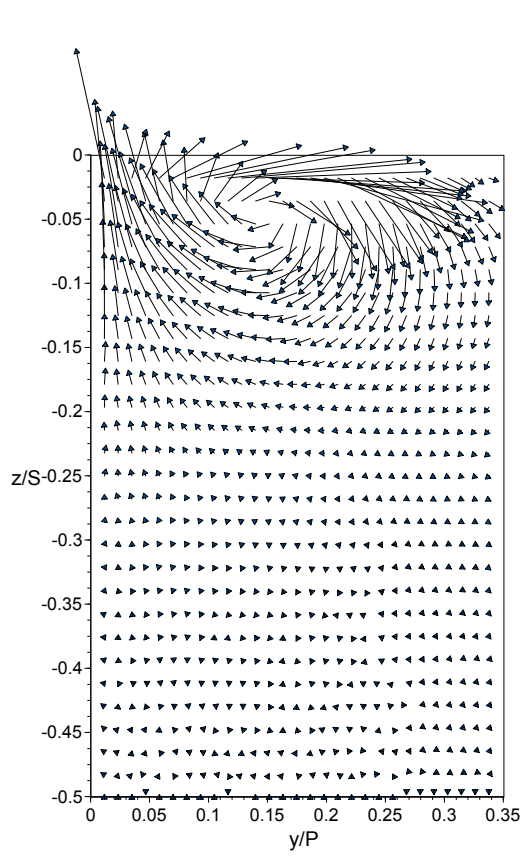


Figure C105. PS2 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

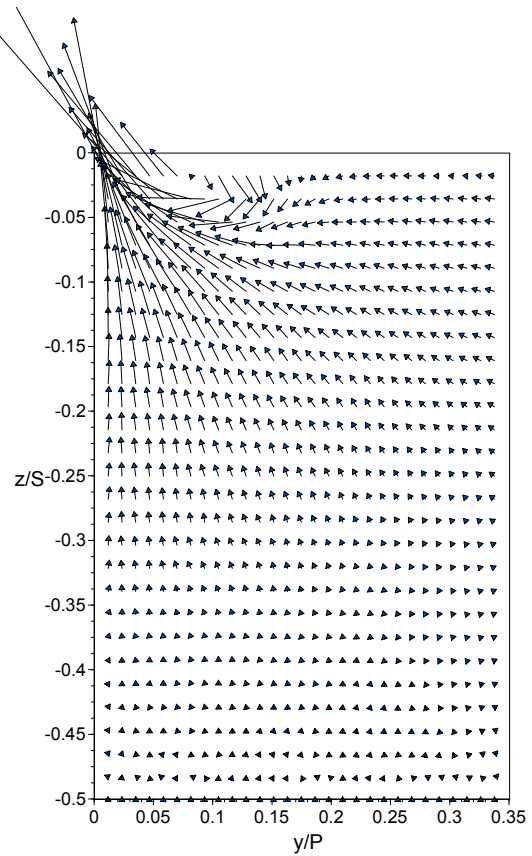


Figure C106. PS2 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

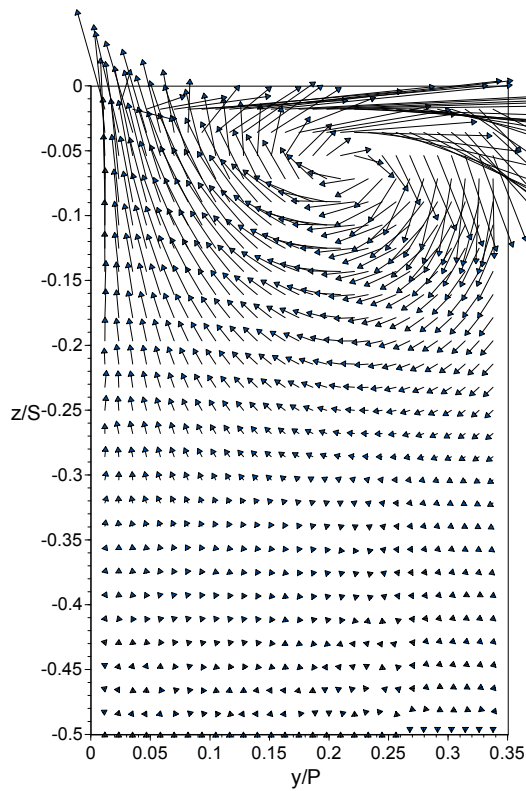


Figure C107. PS2 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

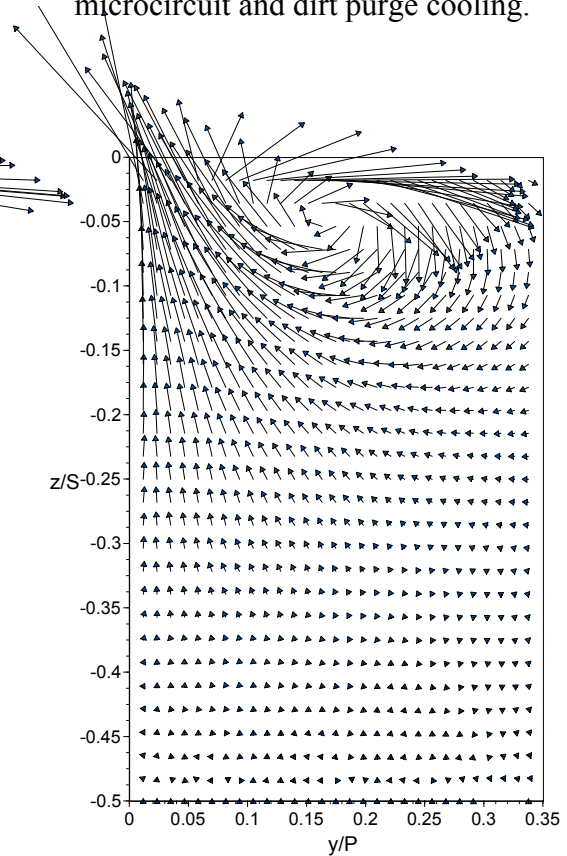


Figure C108. PS2 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

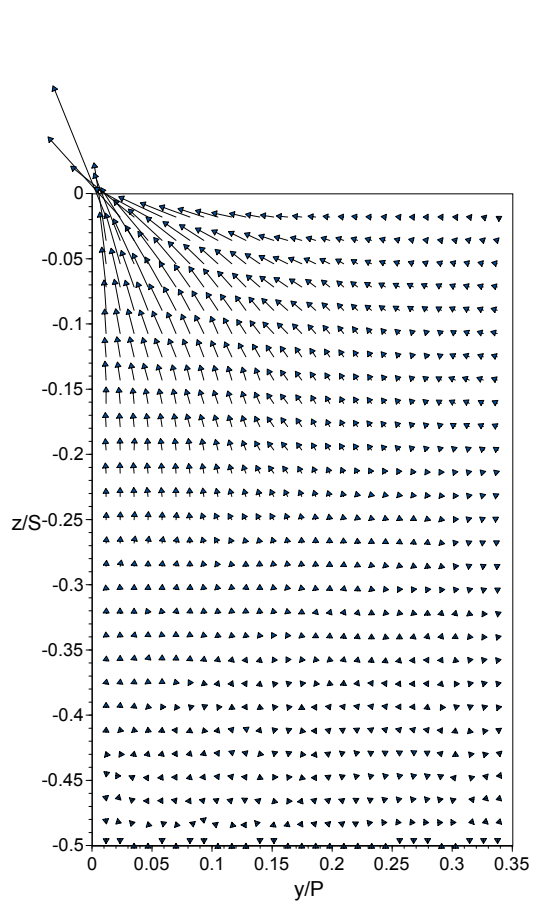


Figure C109. PS3 - Small tip gap, flat tip.

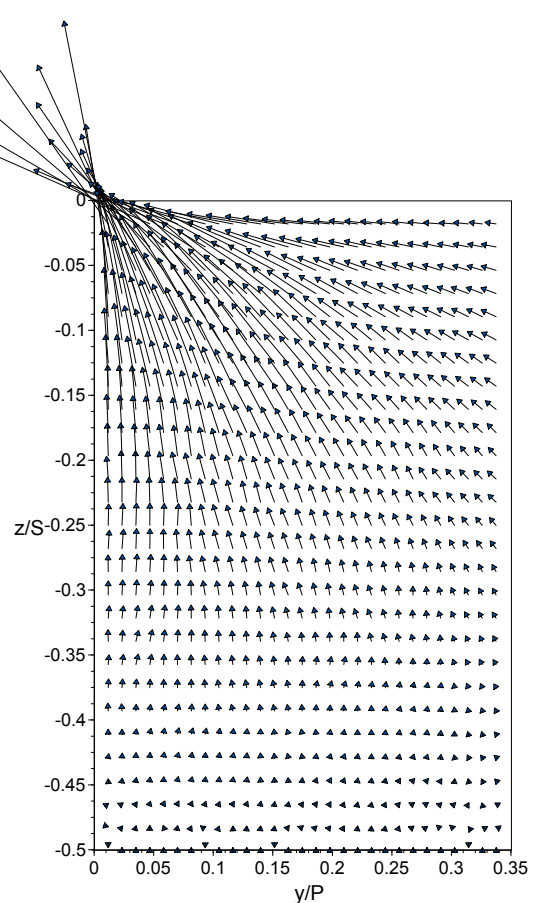


Figure C110. PS3 - Large tip gap, flat tip.

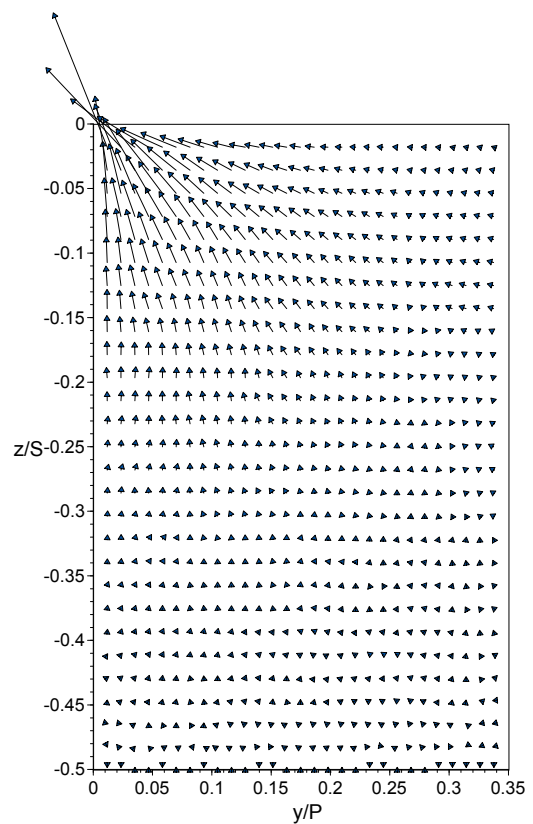


Figure C111. PS3 - Small tip gap, dirt purge cavity, no cooling.

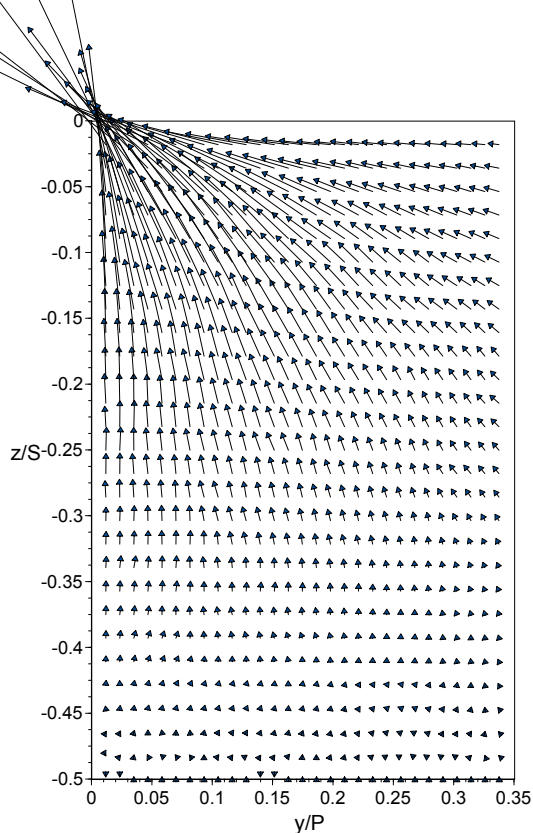


Figure C112. PS3 - Large tip gap, dirt purge cavity, no cooling.

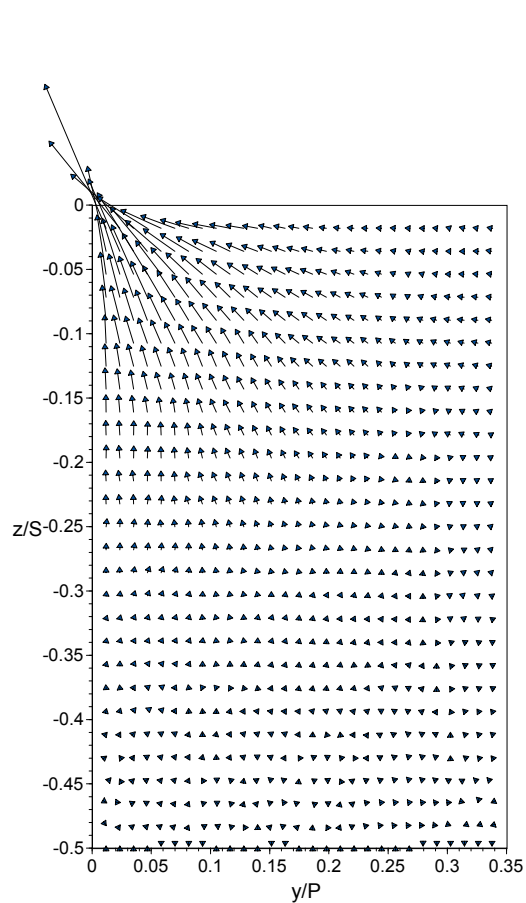


Figure C113. PS3 - Small tip gap, 0.19% dirt purge cooling.

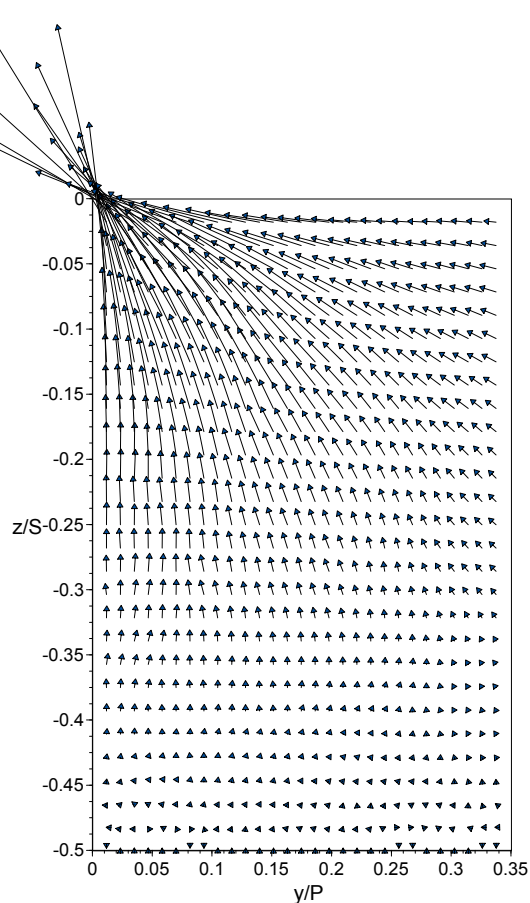


Figure C114. PS3 - Large tip gap, 0.19% dirt purge cooling.

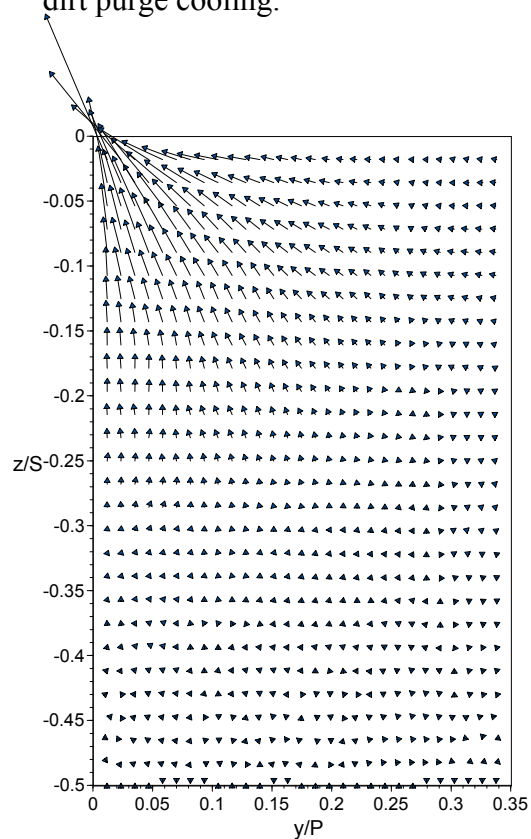


Figure C115. PS3 - Small tip gap, 0.29% dirt purge cooling.

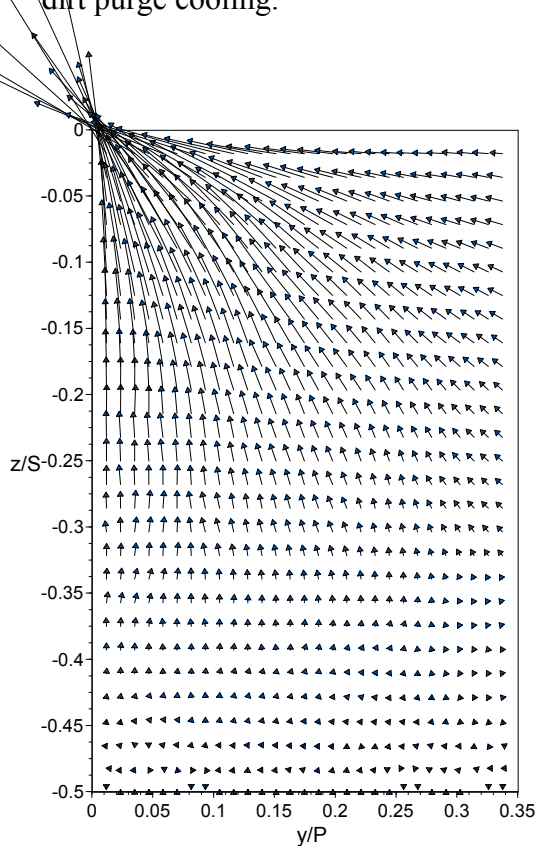


Figure C116. PS3 - Large tip gap, 0.29% dirt purge cooling.

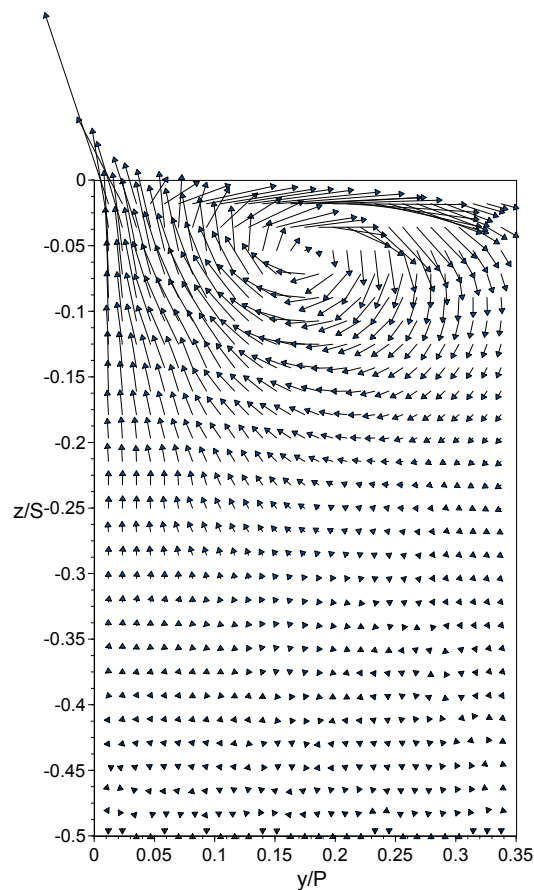


Figure C117. PS3 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

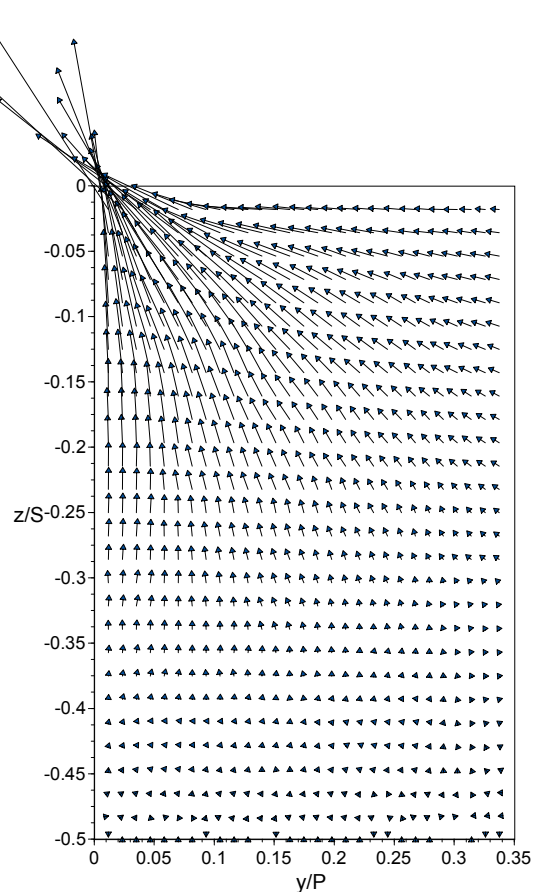


Figure C118. PS3 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

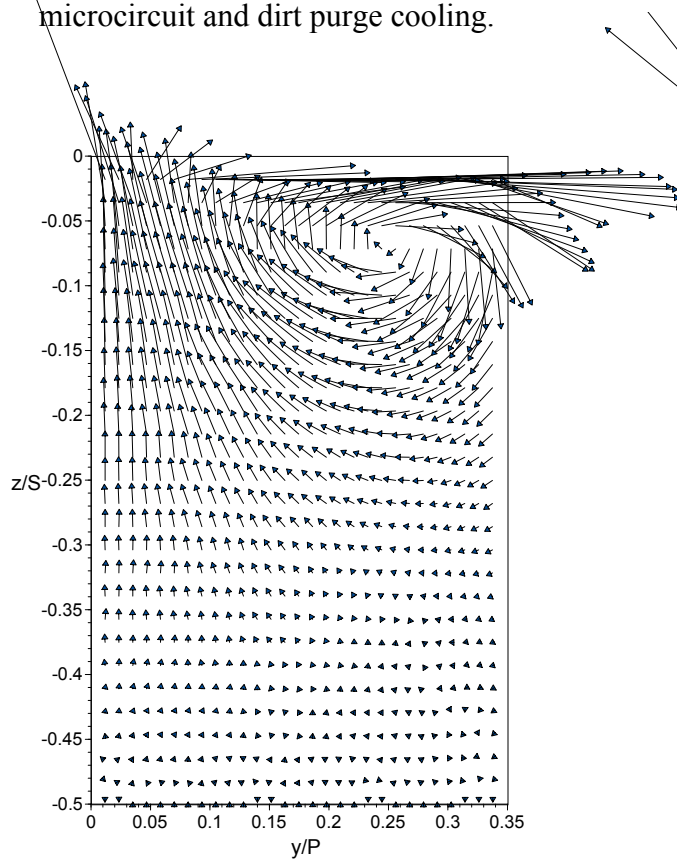


Figure C119. PS3 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

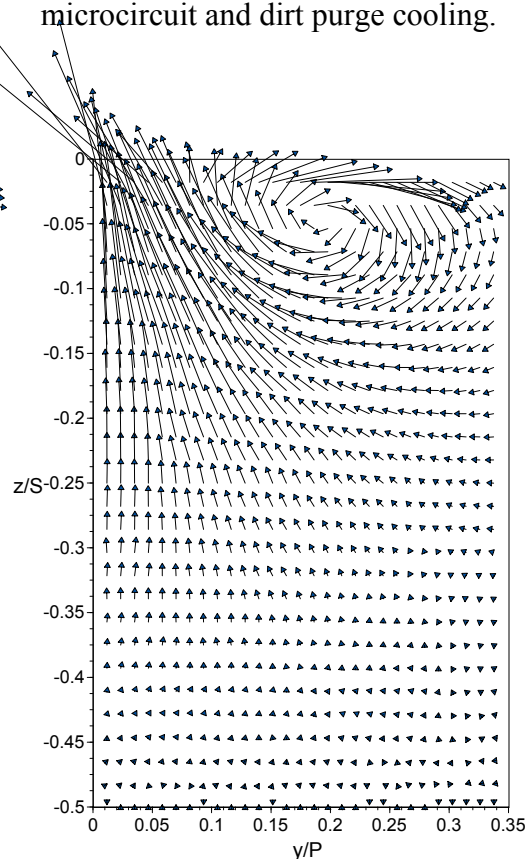


Figure C120. PS3 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

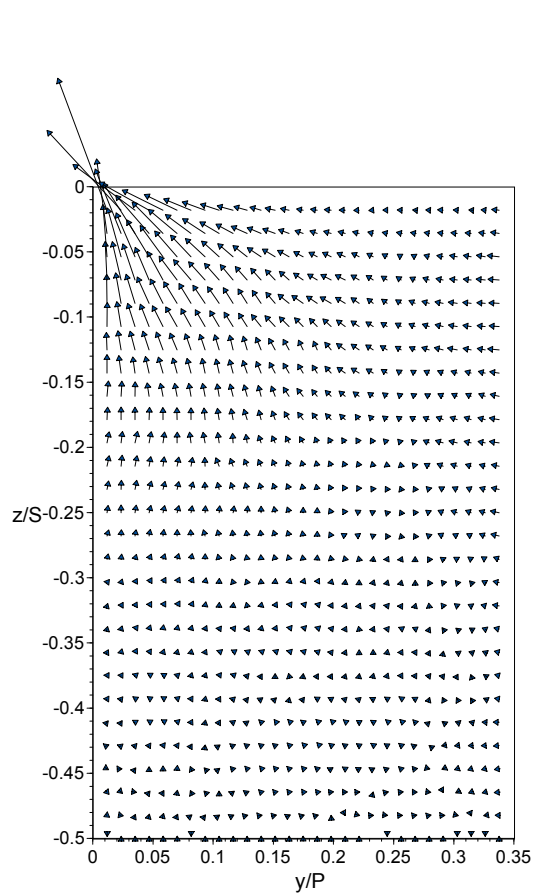


Figure C121. PS4 - Small tip gap, flat tip.

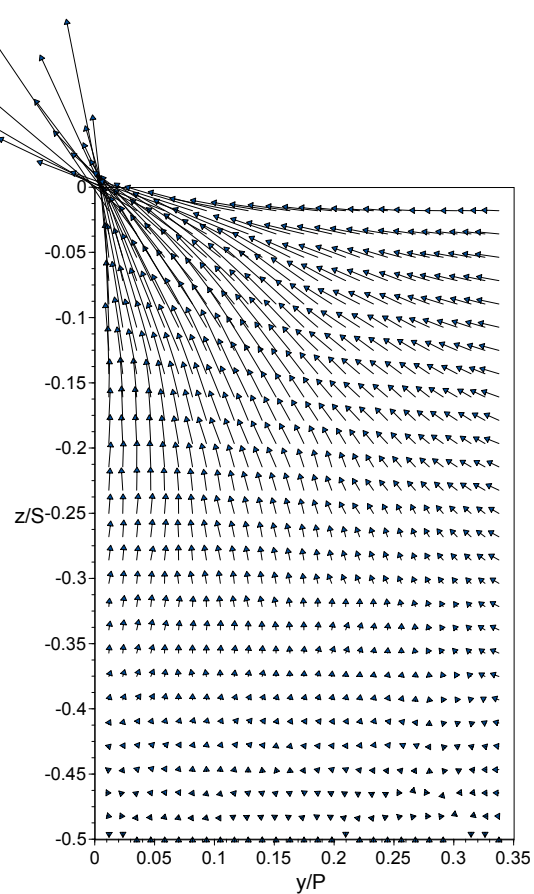


Figure C122. PS4 - Large tip gap, flat tip.

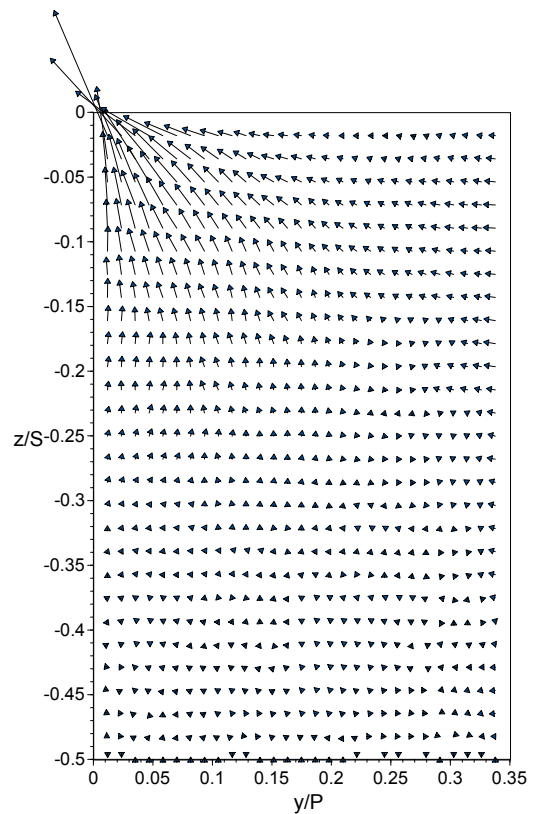


Figure C123. PS4 - Small tip gap, dirt purge cavity, no cooling.

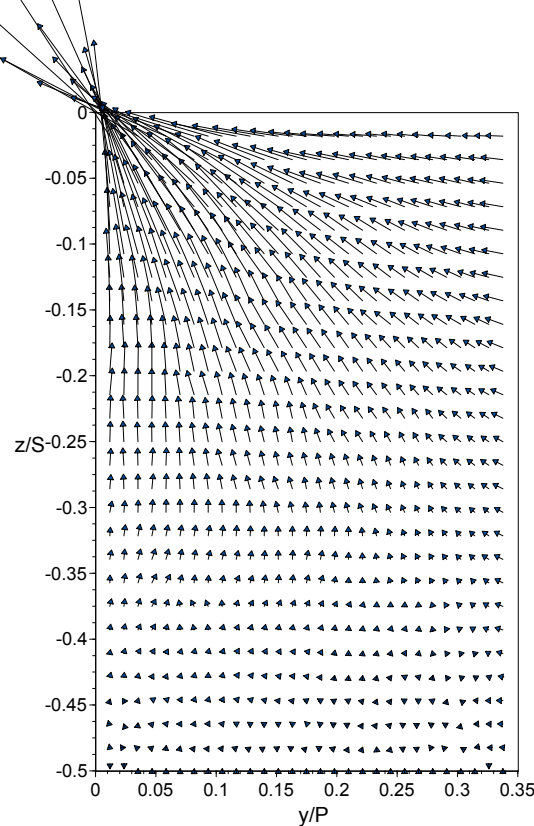


Figure C124. PS4 - Large tip gap, dirt purge cavity, no cooling.

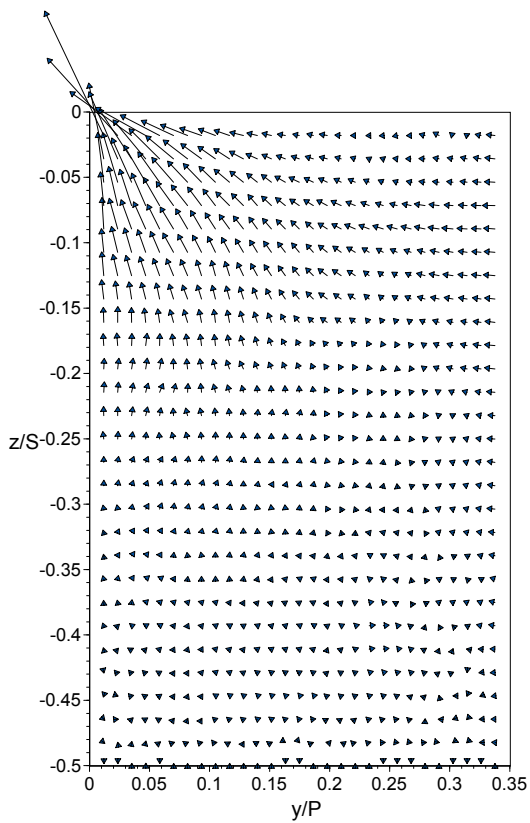


Figure C125. PS4 - Small tip gap, 0.19% dirt purge cooling.

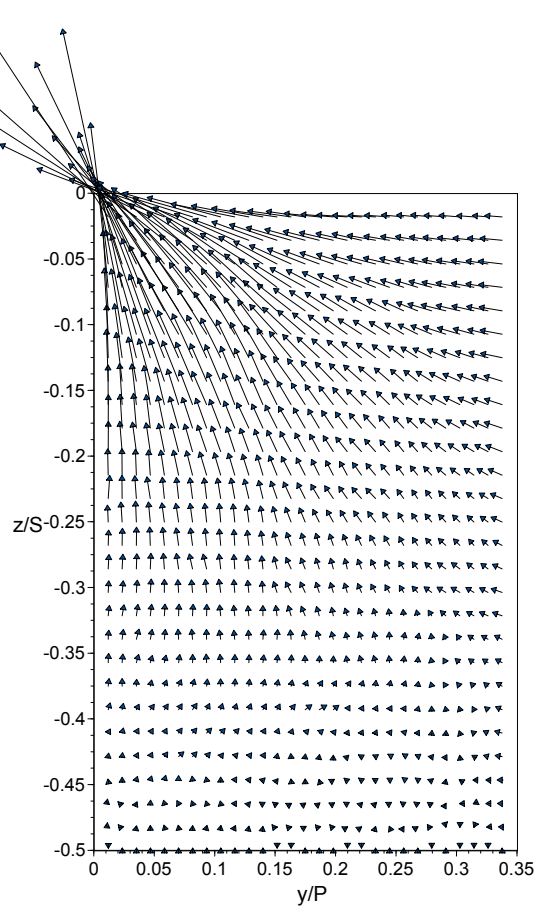


Figure C126. PS4 - Large tip gap, 0.19% dirt purge cooling.

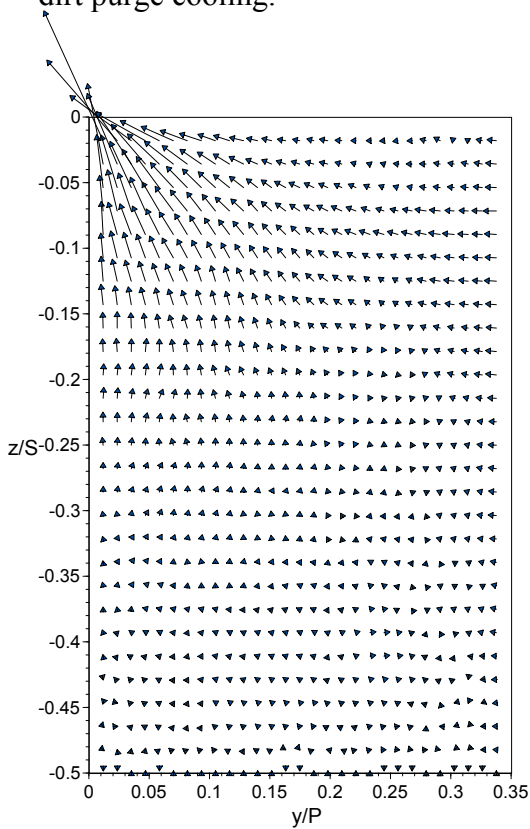


Figure C127. PS4 - Small tip gap, 0.29% dirt purge cooling.

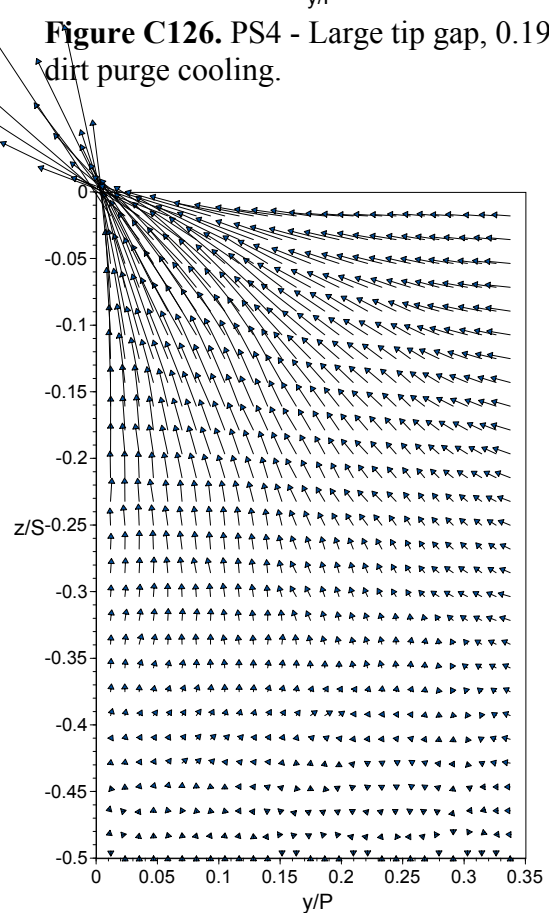


Figure C128. PS4 - Large tip gap, 0.29% dirt purge cooling.

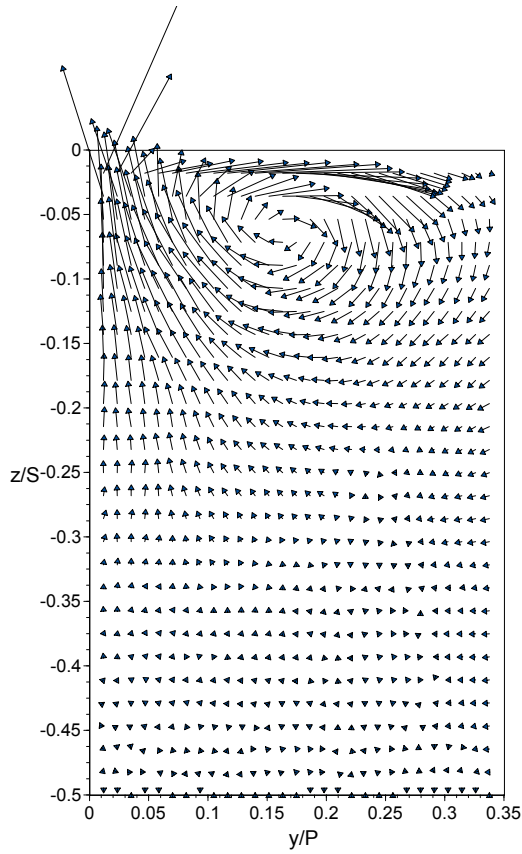


Figure C129. PS4 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

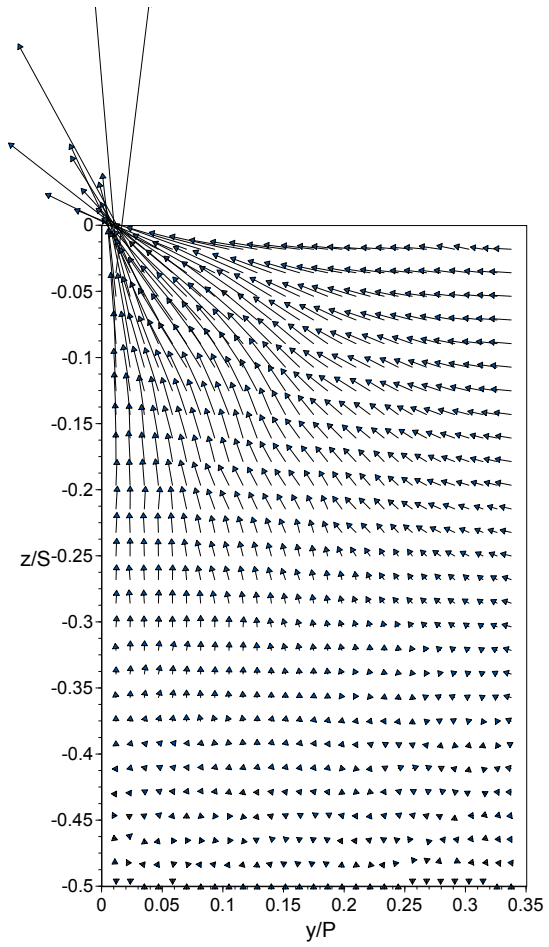


Figure C130. PS4 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

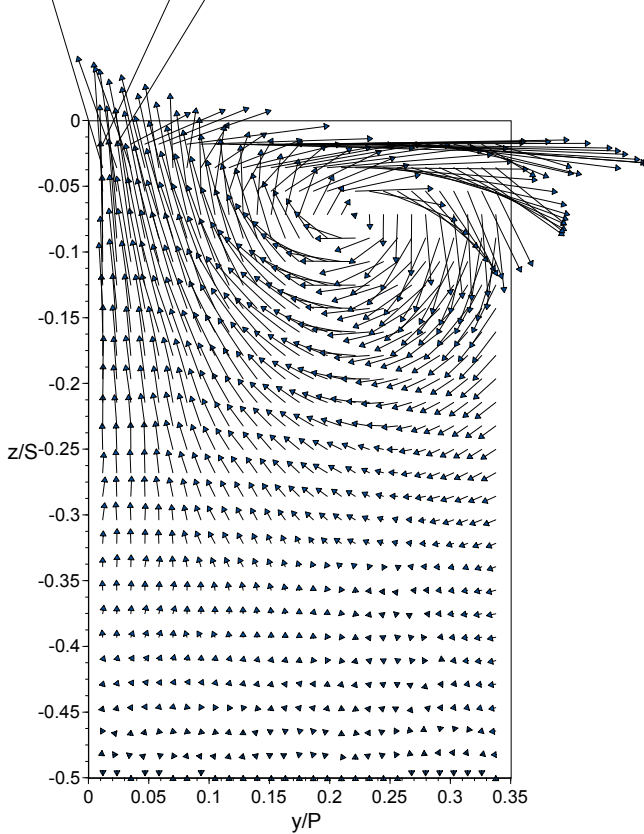


Figure C131. PS4 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

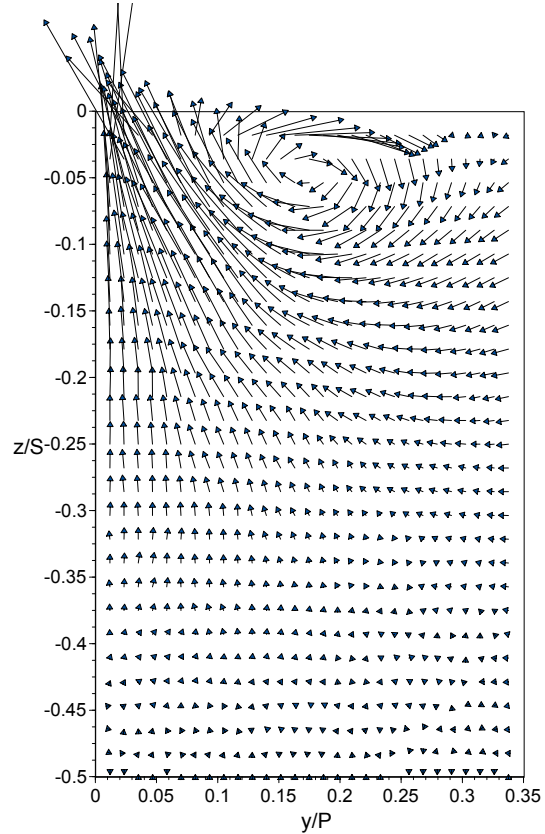


Figure C132. PS4 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

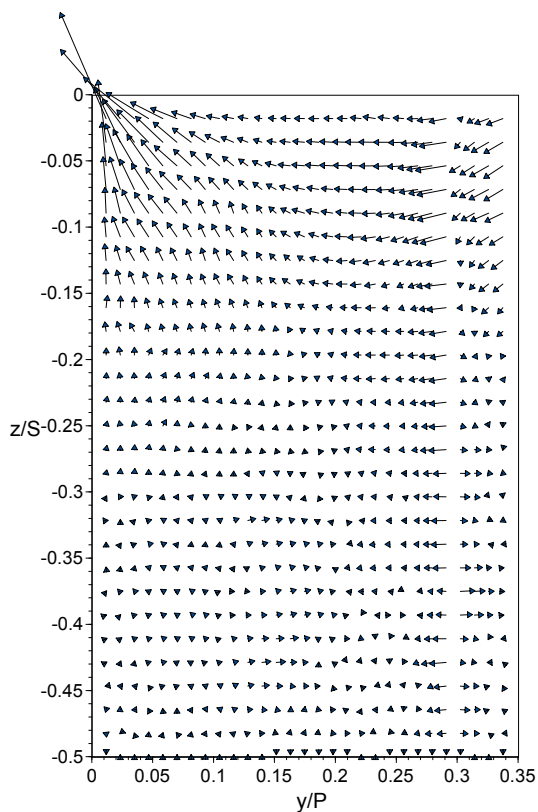


Figure C133. PS5 - Small tip gap, flat tip.

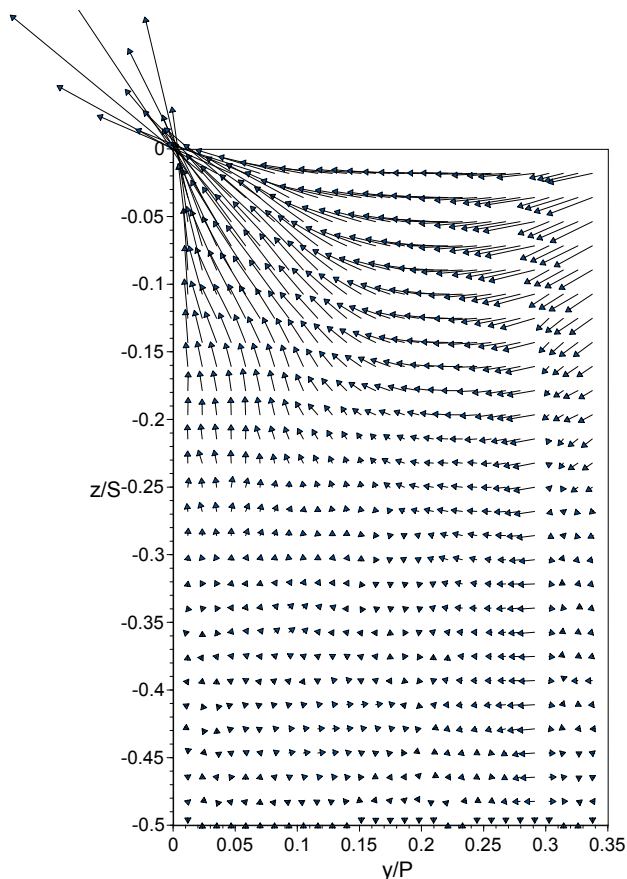


Figure C134. PS5 - Large tip gap, flat tip.

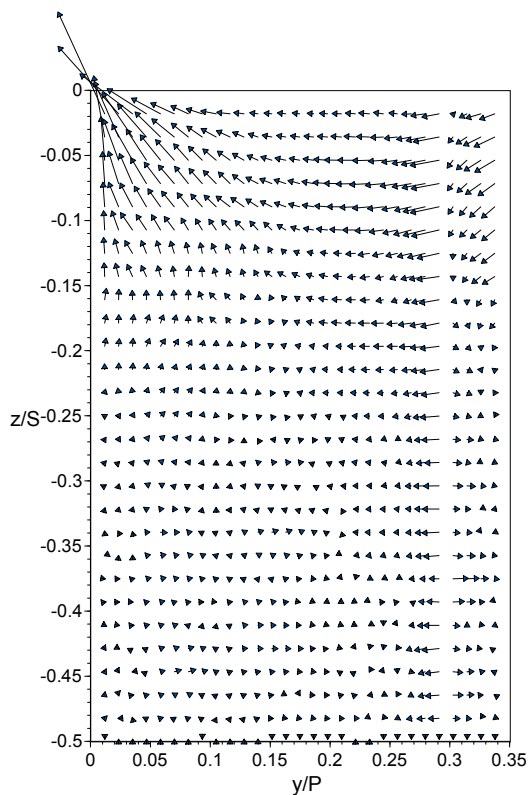


Figure C135. PS5 - Small tip gap, dirt purge cavity, no cooling.

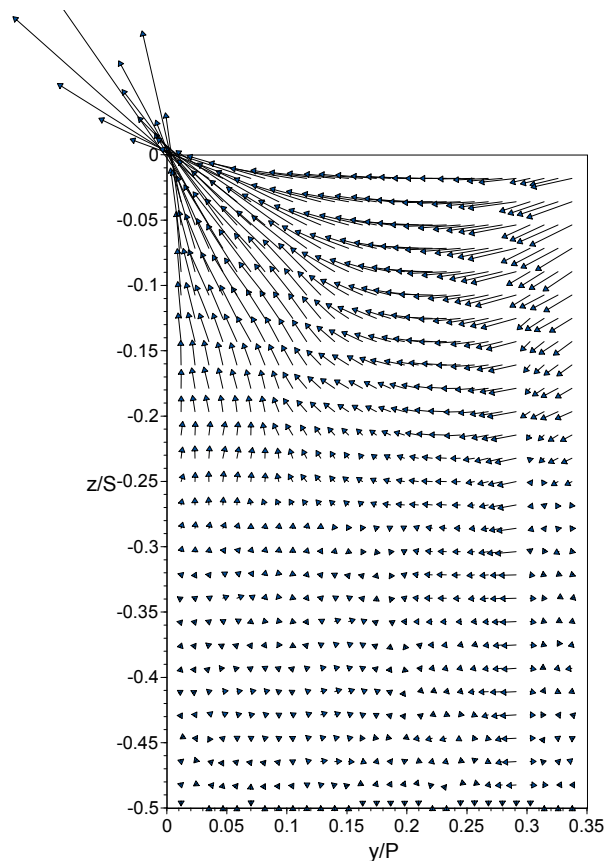


Figure C136. PS5 - Large tip gap, dirt purge cavity, no cooling.

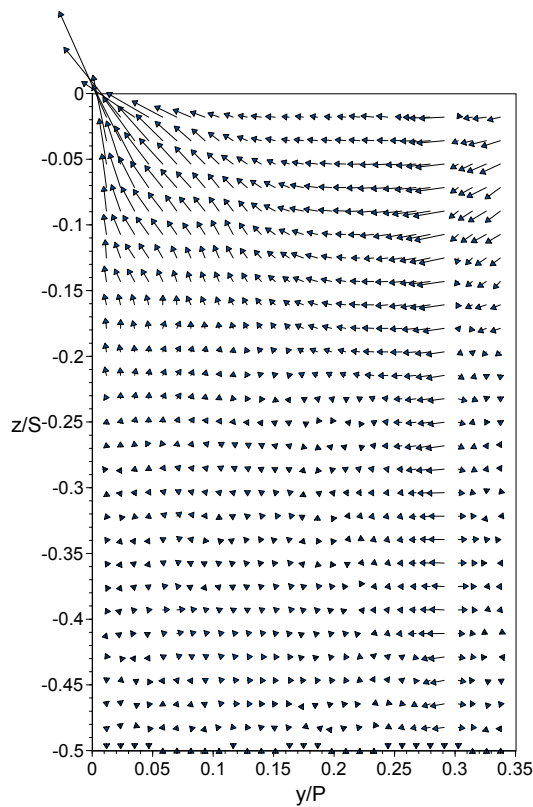


Figure C137. PS5 - Small tip gap, 0.19% dirt purge cooling.

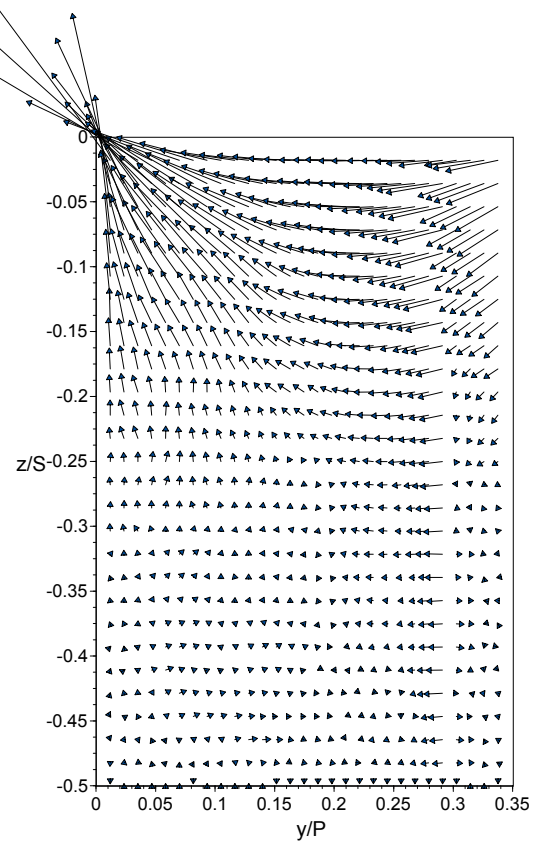


Figure C138. PS5 - Large tip gap, 0.19% dirt purge cooling.

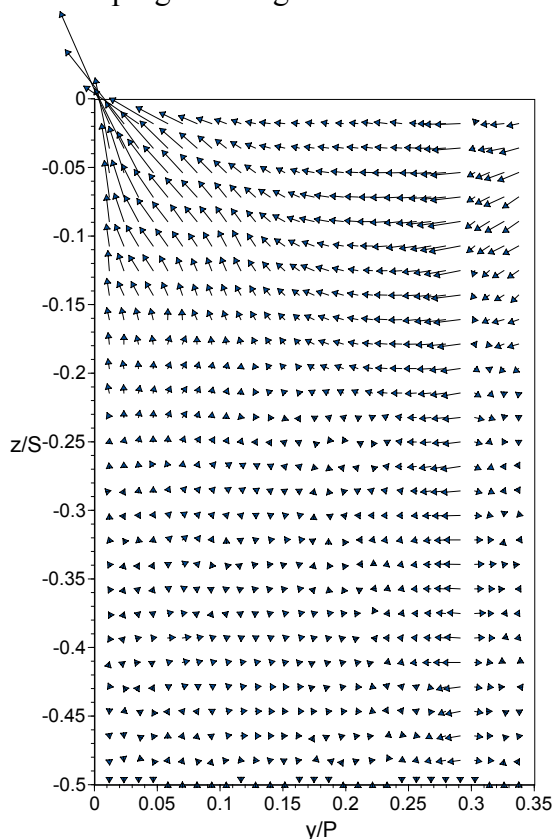


Figure C139. PS5 - Small tip gap, 0.29% dirt purge cooling.

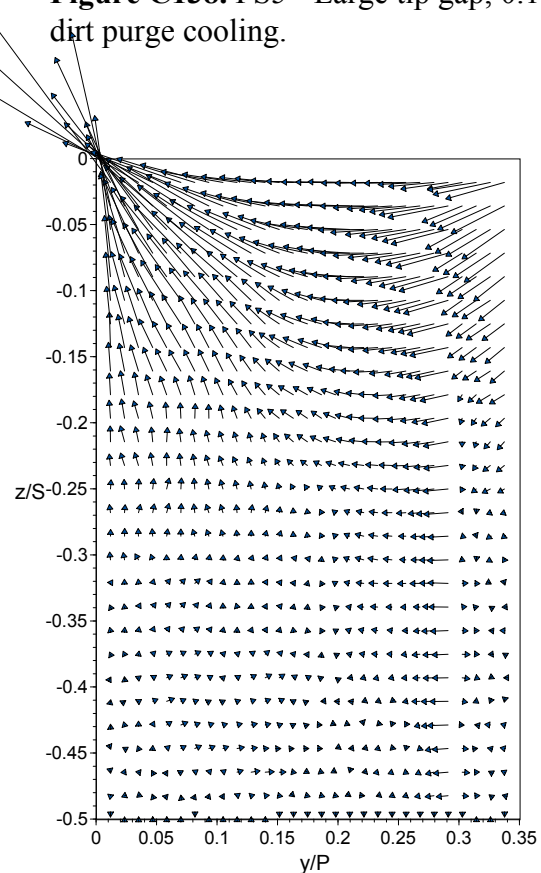


Figure C140. PS5 - Large tip gap, 0.29% dirt purge cooling.

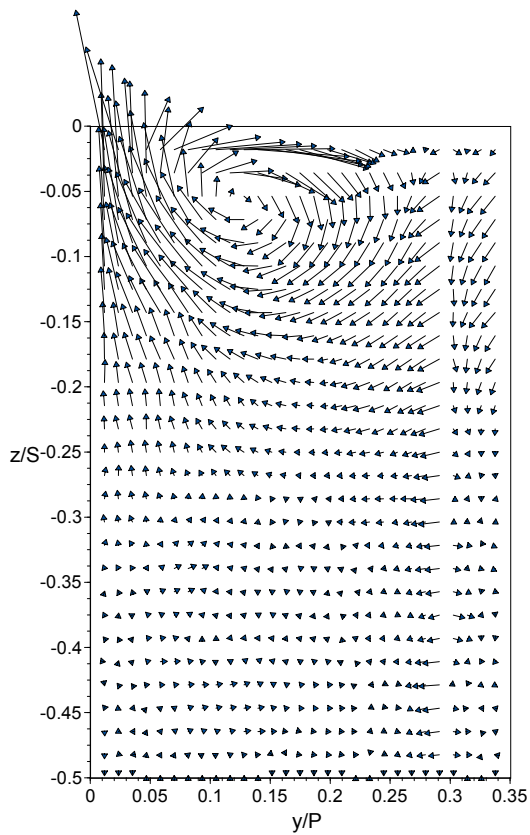


Figure C141. PS5- Small tip gap, 1.0% microcircuit and dirt purge cooling.

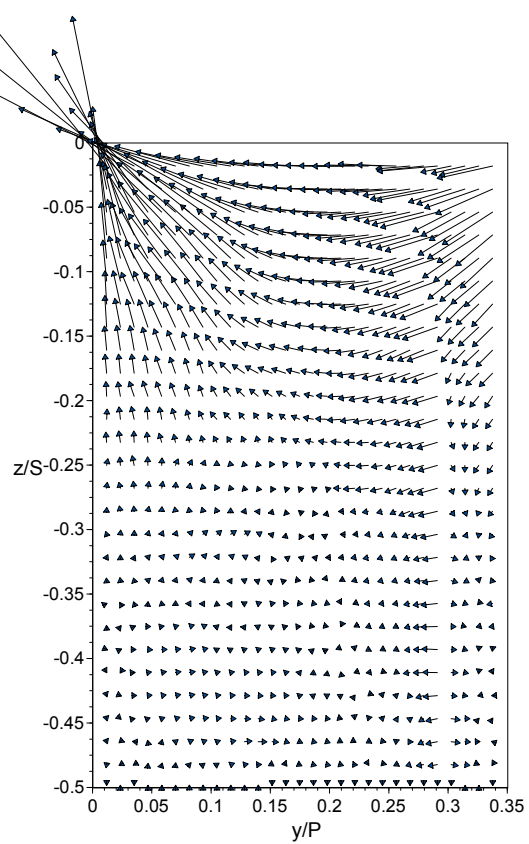


Figure C142. PS5 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

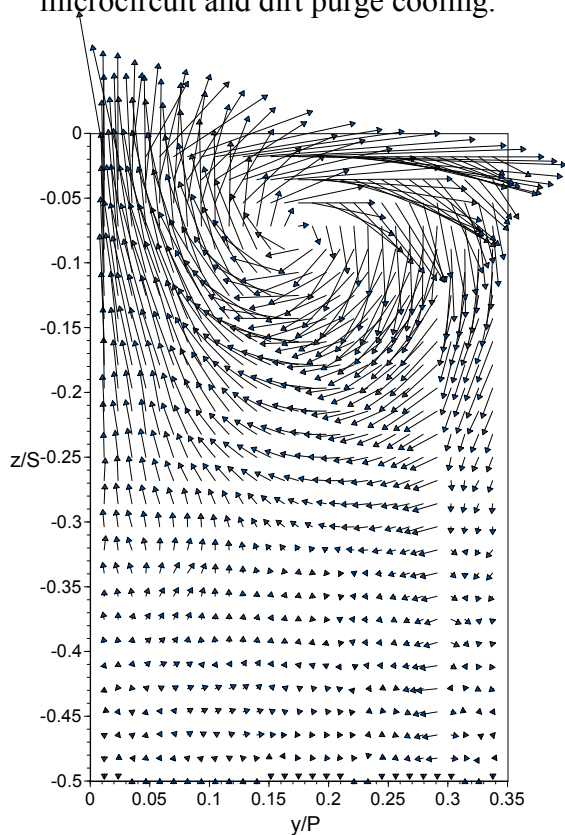


Figure C143. PS5 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

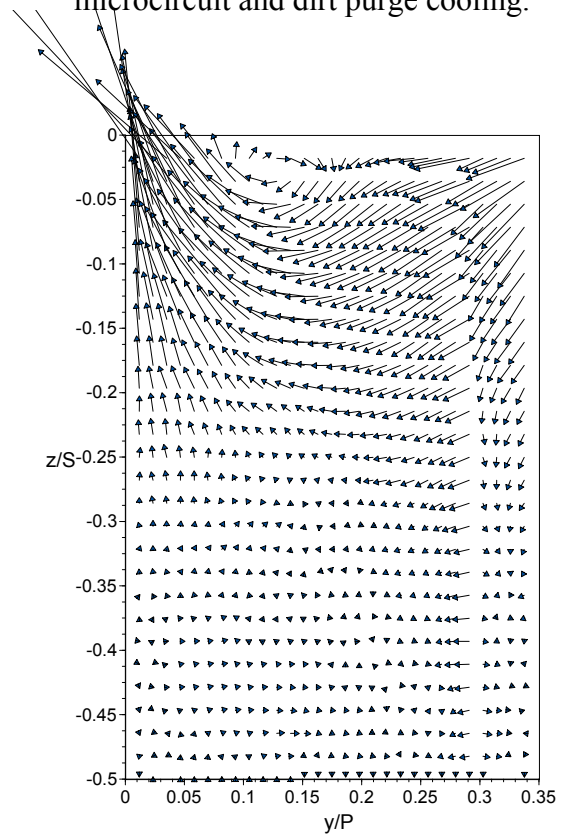


Figure C144. PS5 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

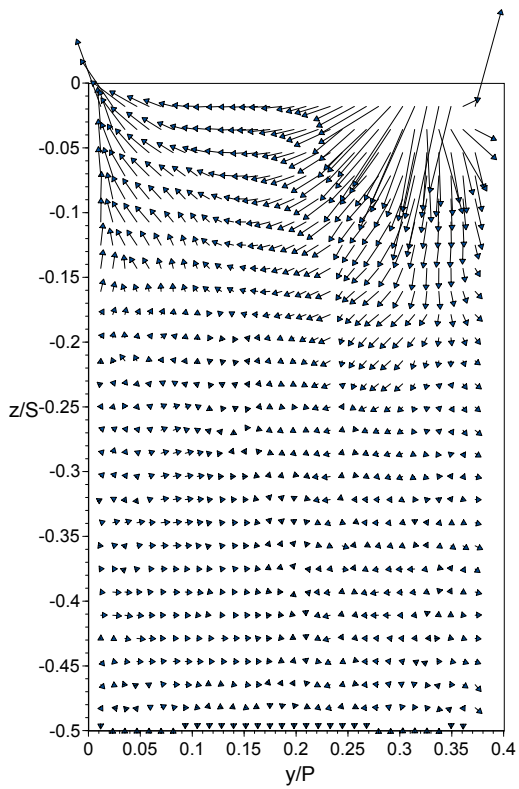


Figure C145. PS6 - Small tip gap, flat tip.

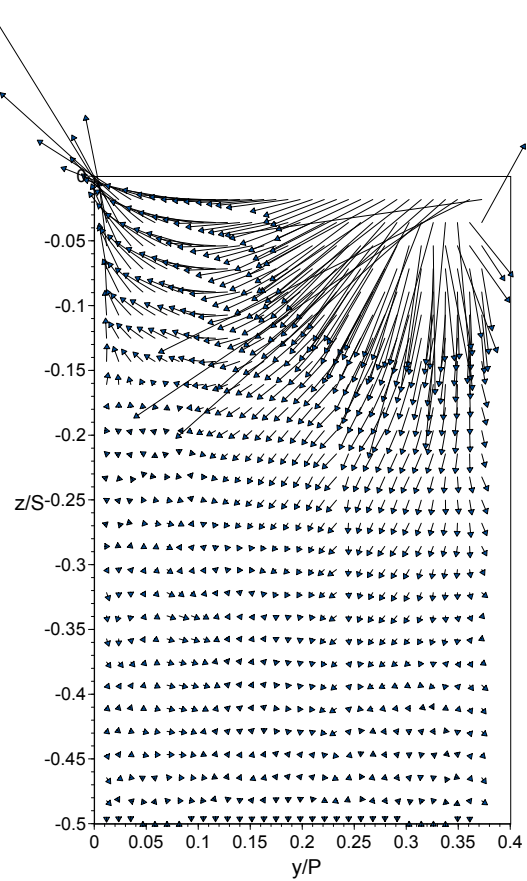


Figure C146. PS6 - Large tip gap, flat tip.

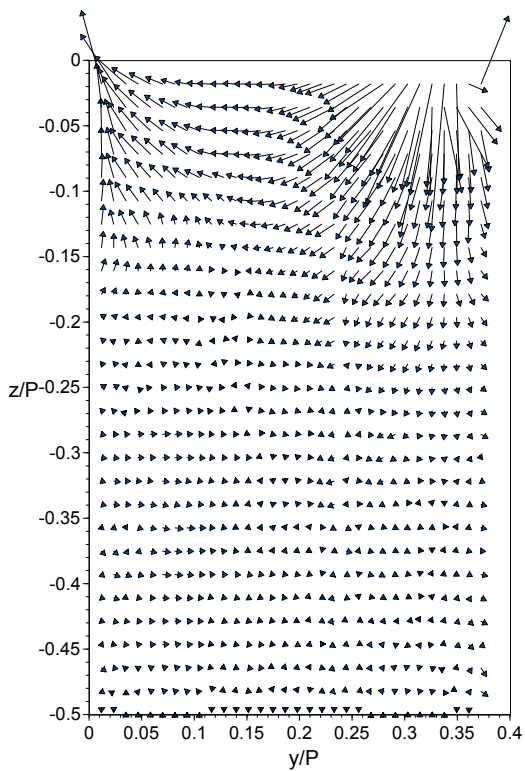


Figure C147. PS6 - Small tip gap, dirt purge cavity, no cooling.

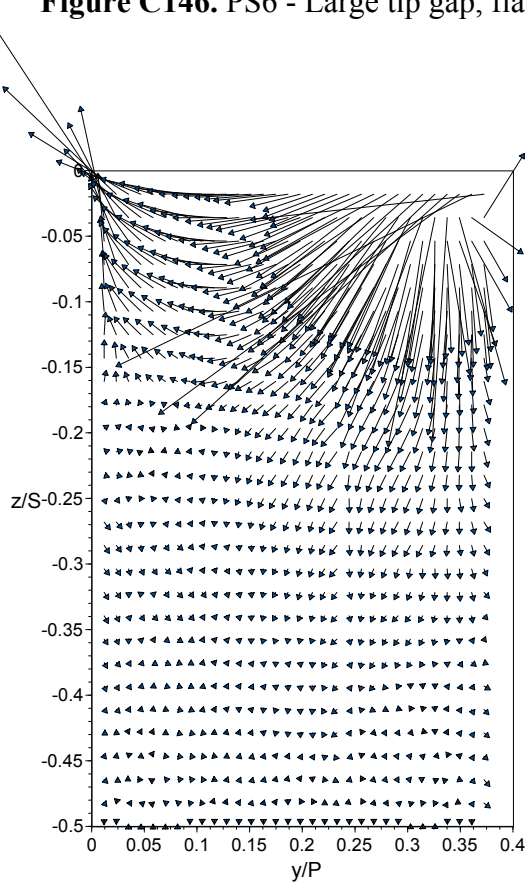


Figure C148. PS6 - Large tip gap, dirt purge cavity, no cooling.

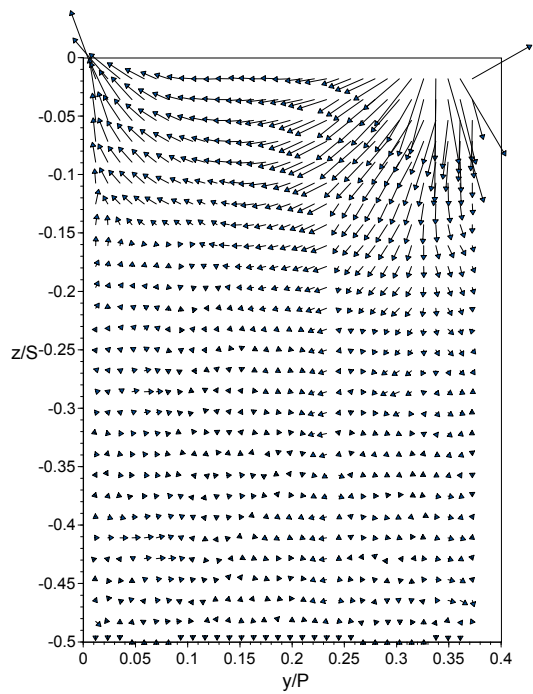


Figure C149. PS6 - Small tip gap, 0.19% dirt purge cooling.

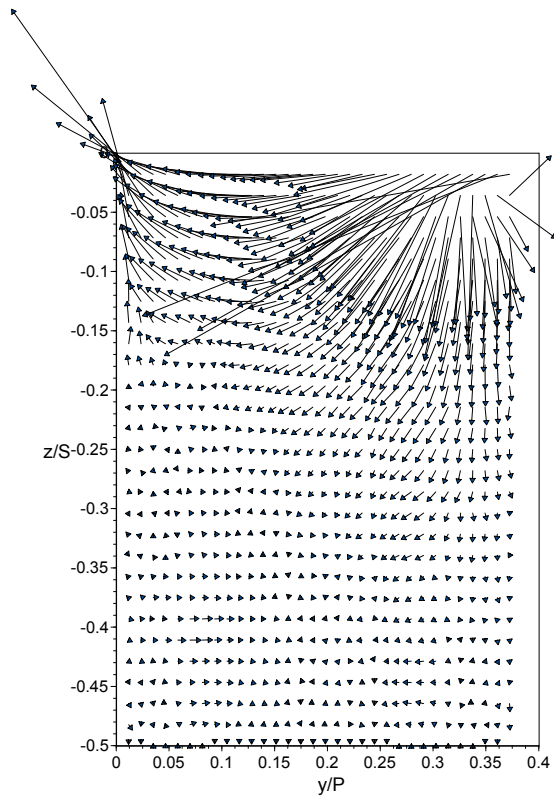


Figure C150. PS6 - Large tip gap, 0.19% dirt purge cooling.

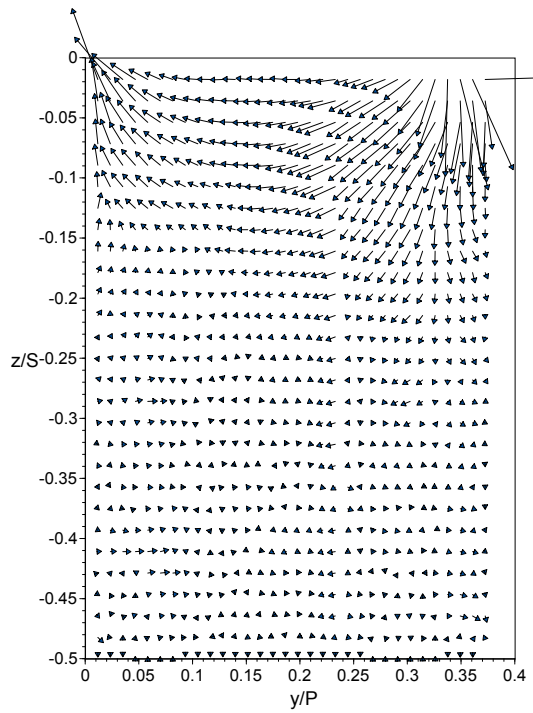


Figure C151. PS6 - Small tip gap, 0.29% dirt purge cooling.

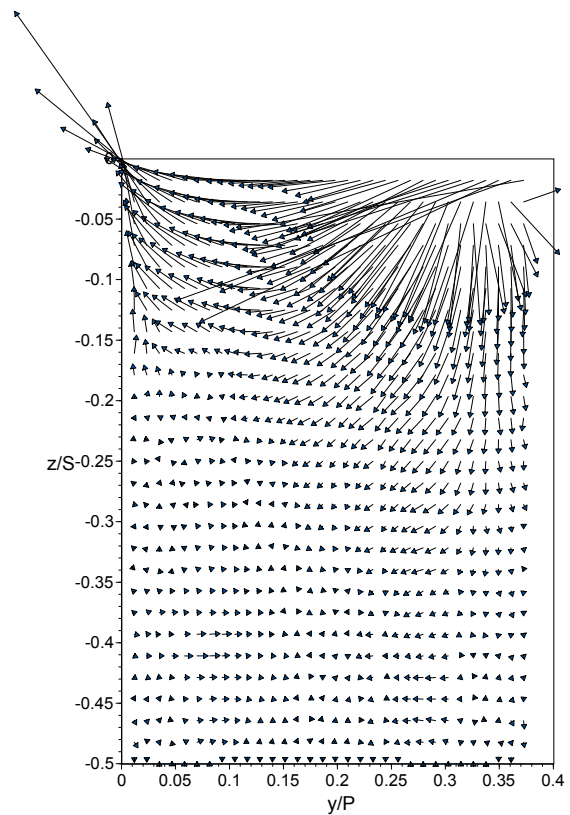


Figure C152. PS6 - Large tip gap, 0.29% dirt purge cooling.

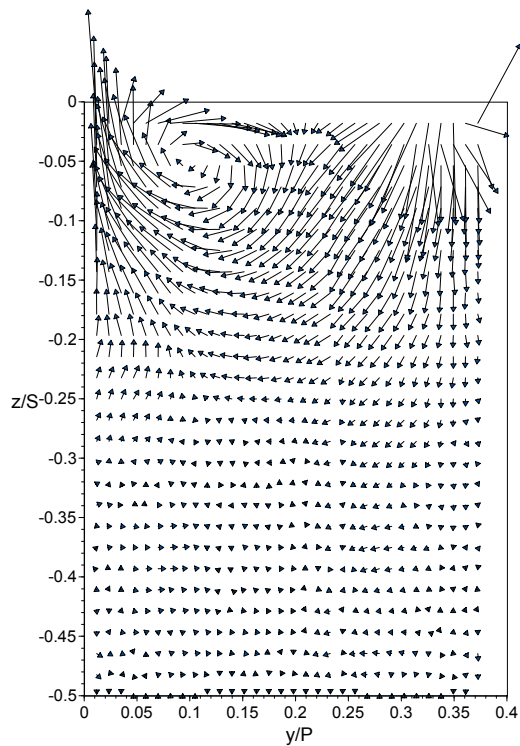


Figure C153 PS6 - Small tip gap, 1.0% microcircuit and dirt purge cooling.

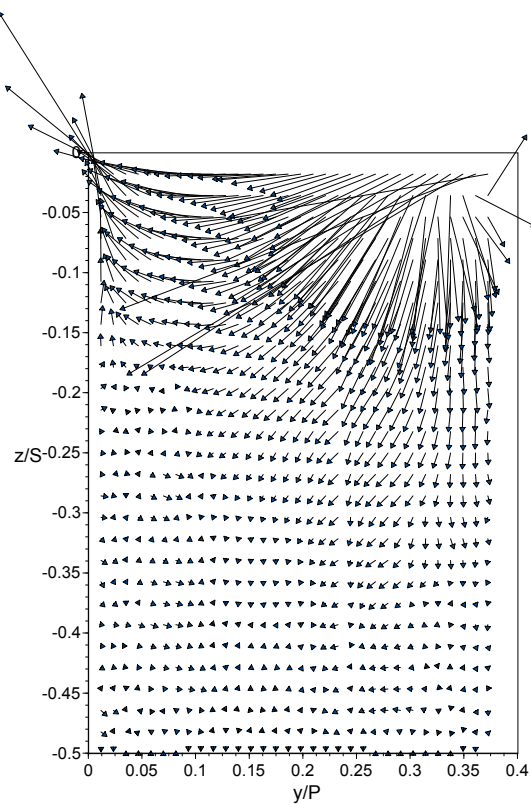


Figure C154. PS6 - Large tip gap, 1.0% microcircuit and dirt purge cooling.

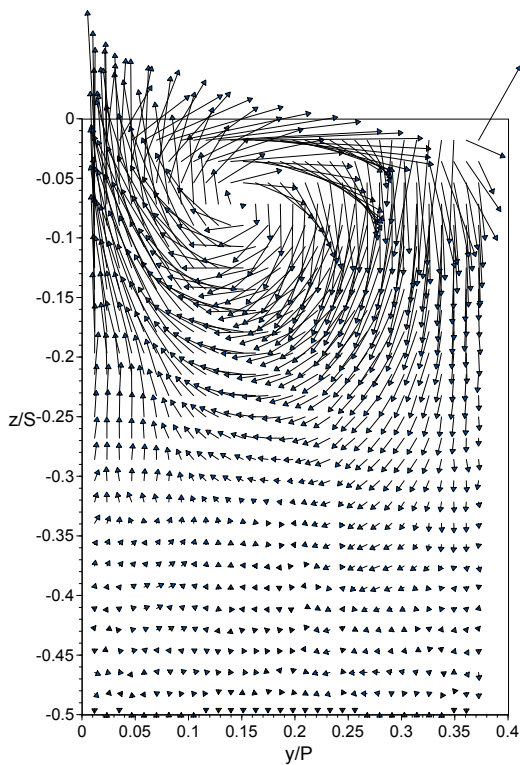


Figure C155. PS6 - Small tip gap, 1.5% microcircuit and dirt purge cooling.

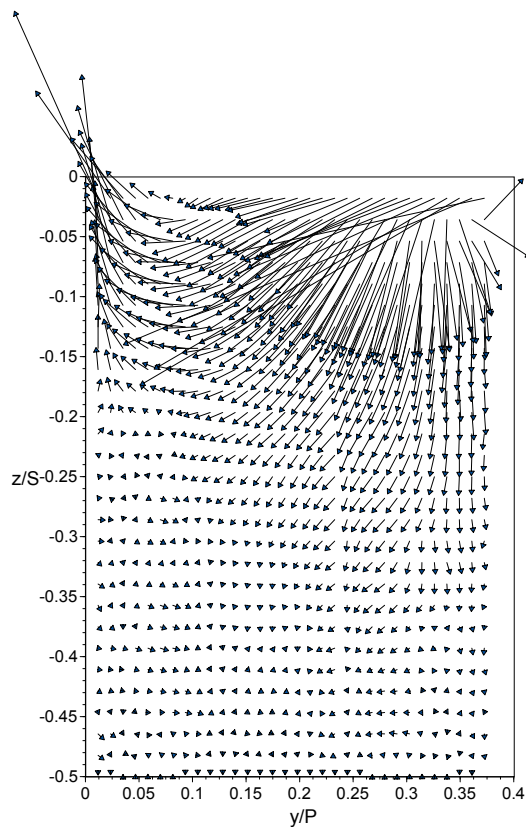


Figure C156. PS6 - Large tip gap, 1.5% microcircuit and dirt purge cooling.

Appendix D: Platform Secondary Flow – Pressure side and Suction side planes.

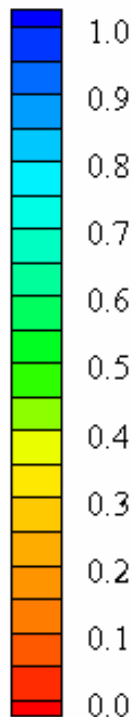
Eight planes were defined around the blade platform to study secondary flow patterns and thermal contours throughout the turbine passage. A total of five suction side planes and three pressure side planes were positioned normal to the blade surface and are shown in Figure D0. A detailed discussion concerning the methodologies behind this secondary flow visualization technique is presented in Section 4.5 with several planes shown in Chapter 6. The following appendix contains data from six different cases which include cases with a:

1. baseline – no fillet,
2. baseline - fillet,
3. ActiveMC – no microcircuit,
4. ActiveMC,
5. PW6000, and
6. PW4000.

Temperature has been non-dimensionalized in each of the contours plots using the following equation.

$$\Theta = \frac{T_{\infty} - T}{T_{\infty} - T_c} \quad (D-1)$$

The contours shown within this appendix correspond to the temperature bar shown below. Where 1.0 represents the fluid temperature of the coolant and 0.0 represents the temperature of the hot mainstream gases.



Plane	s/s_{\max}	X/B_x
SS1	0.01	0.06
SS2	0.31	0.39
SS3	0.68	0.88
SS4	0.82	0.96
SS5	0.95	0.99
PS1	-0.15	0.07
PS2	-0.51	0.57
PS3	-0.96	0.96

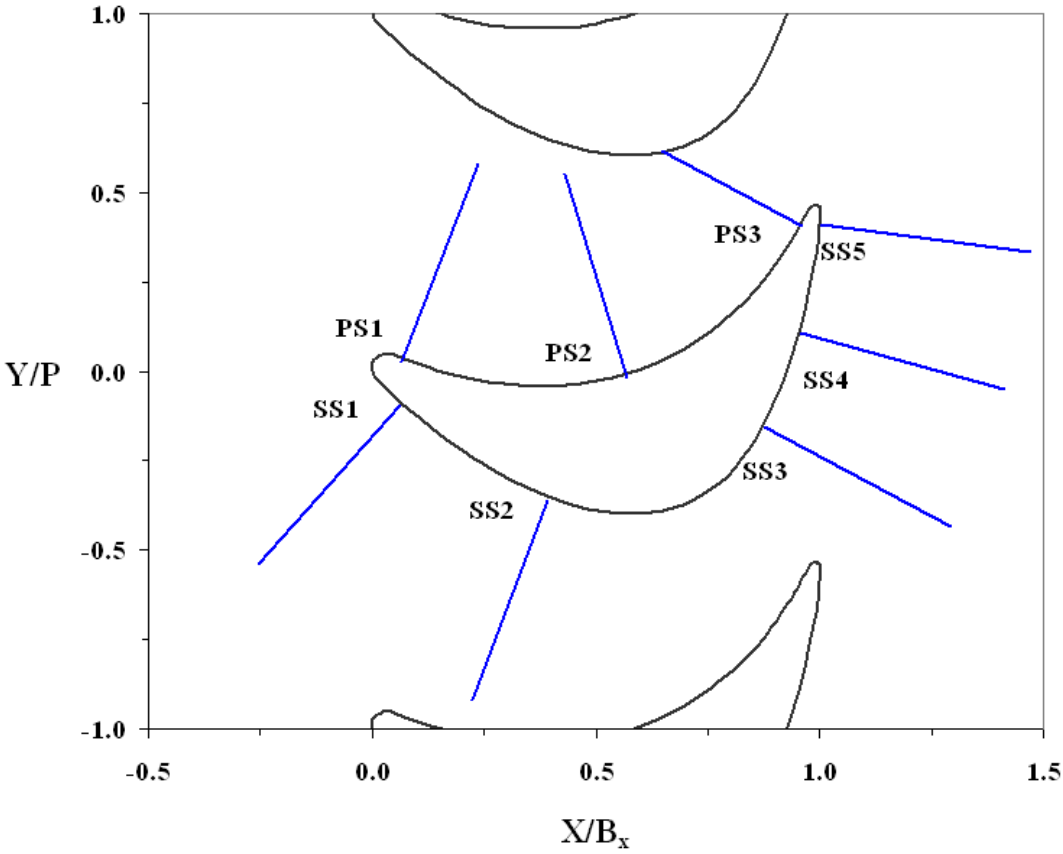


Figure D0. Location of secondary flow planes around the platform geometry.

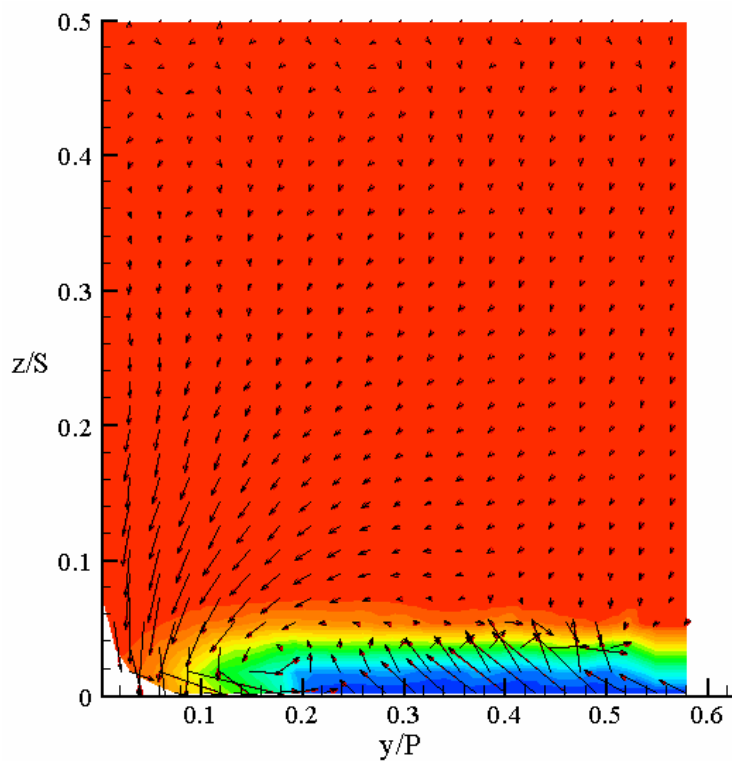


Figure D1. SS1 - ActiveMC.

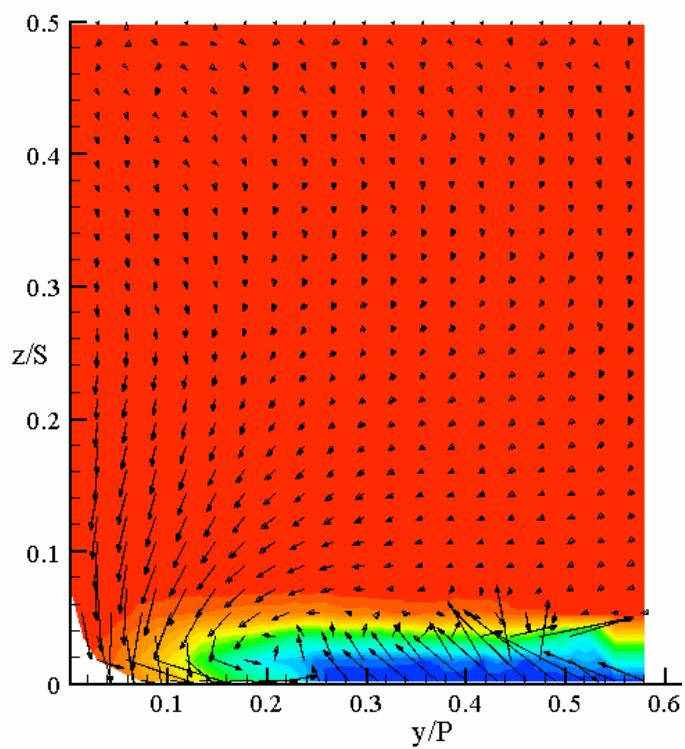


Figure D2. SS1 - ActiveMC
(no microcircuit).

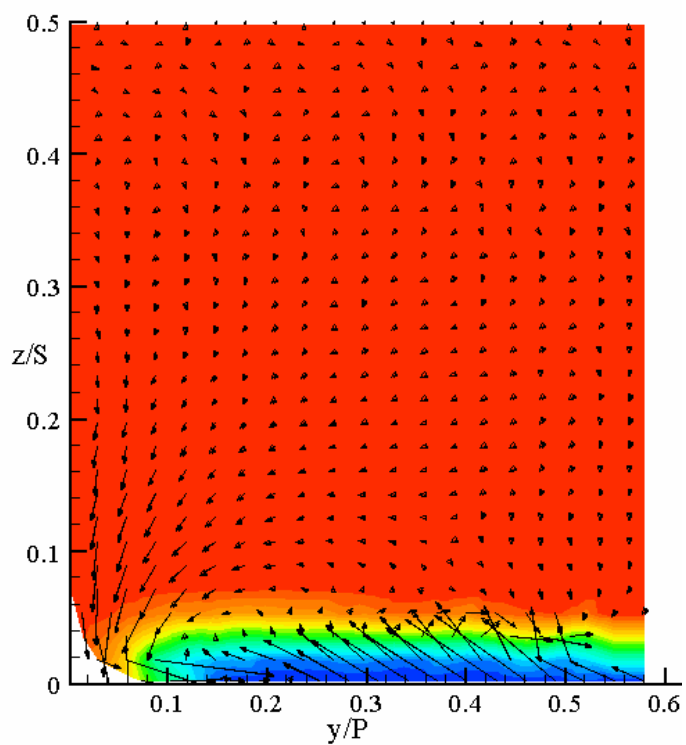


Figure D3. SS1 - PW6000.

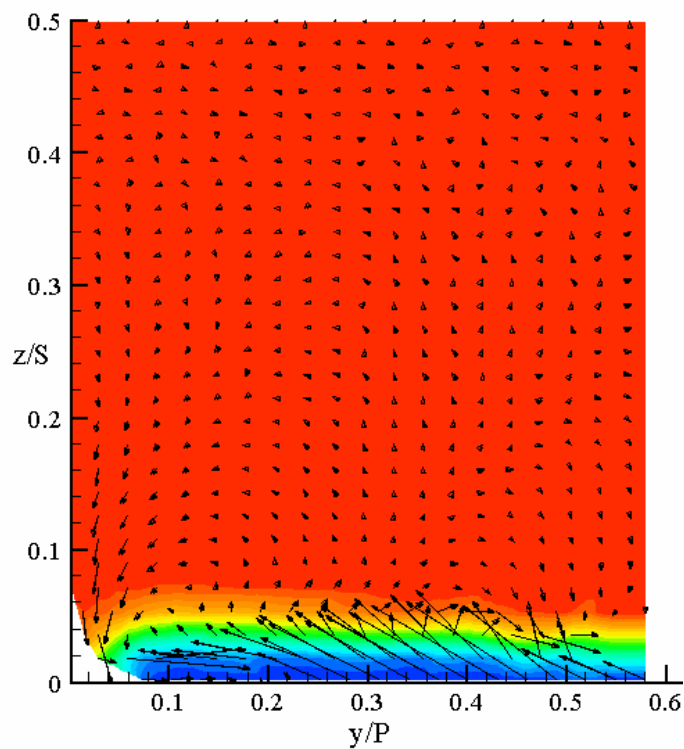


Figure D4. SS1 - PW4000.

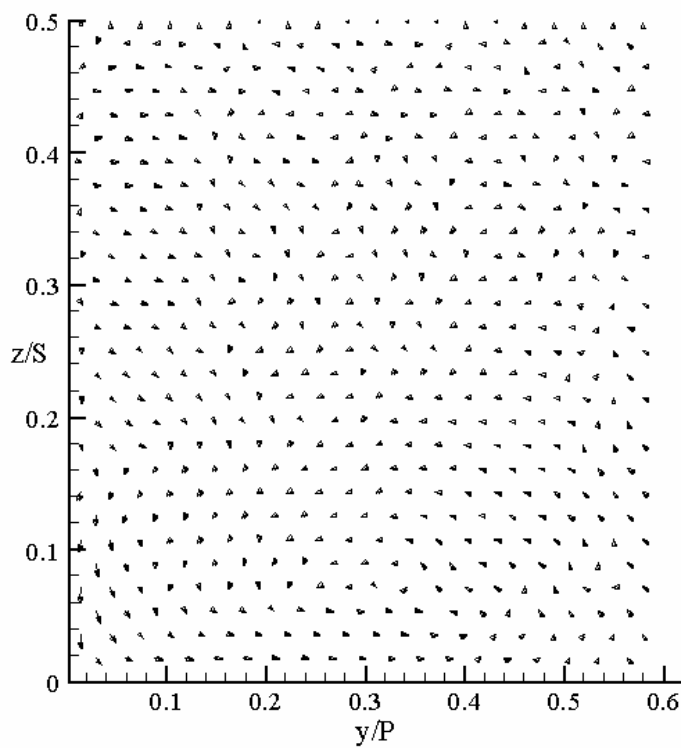


Figure D5. SS1 – Baseline (no fillet).

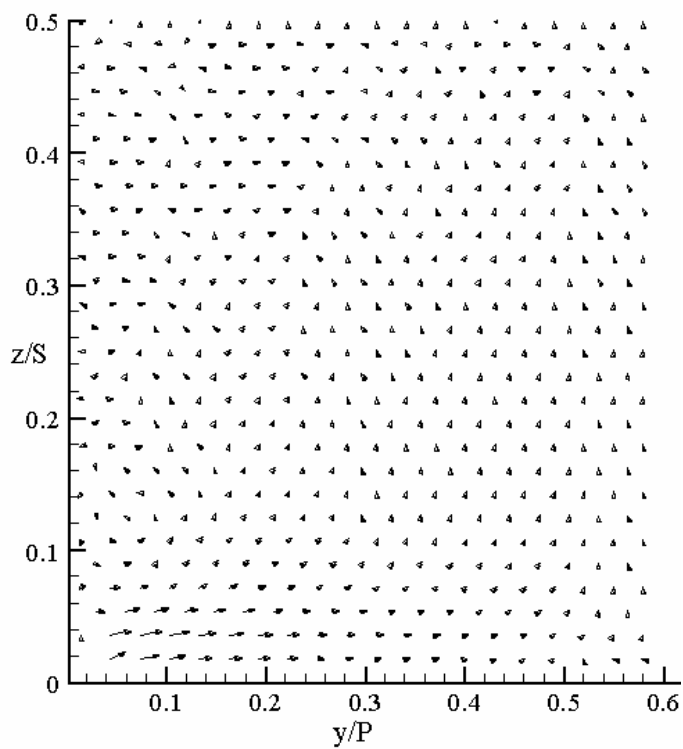


Figure D6. SS1 – Baseline (fillet).

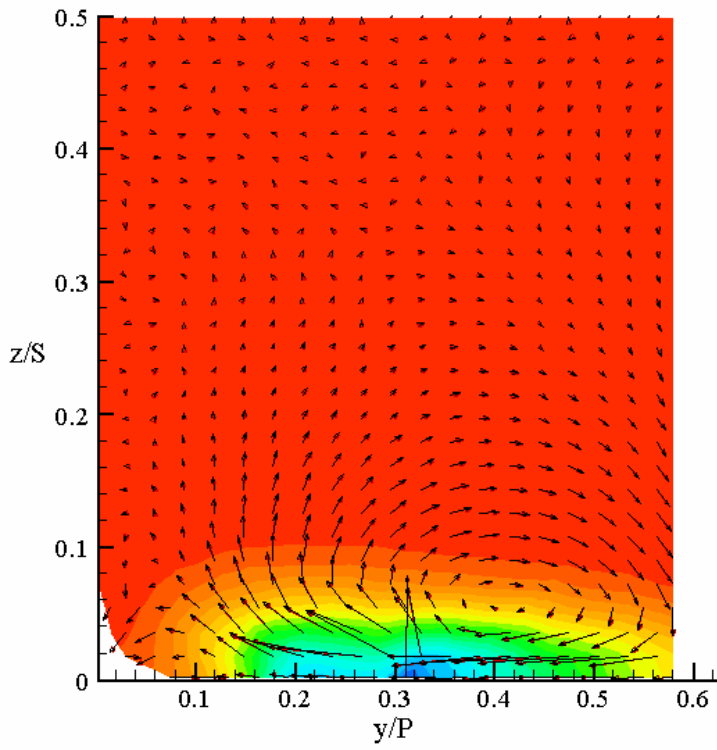


Figure D7. SS2 - ActiveMC.

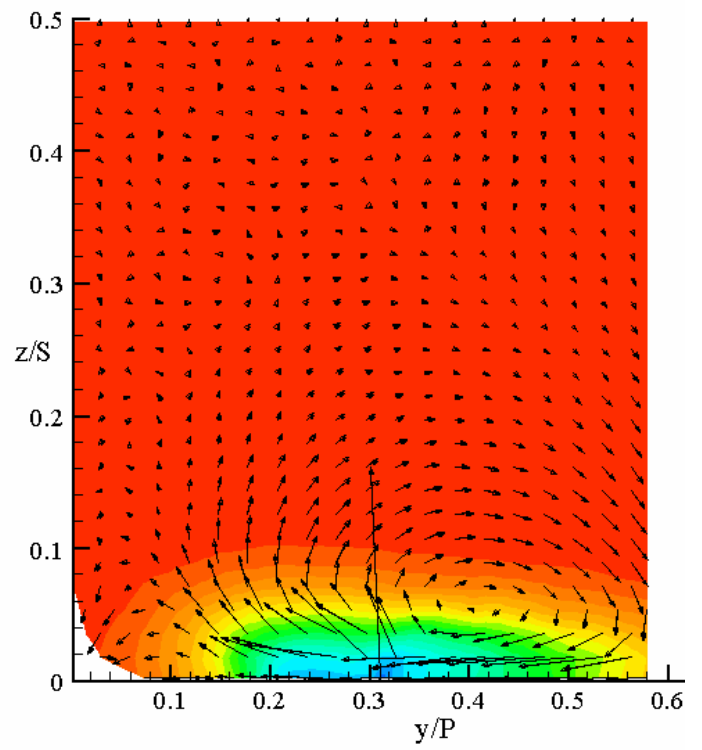


Figure D8. SS2 – ActiveMC
(no microcircuit).

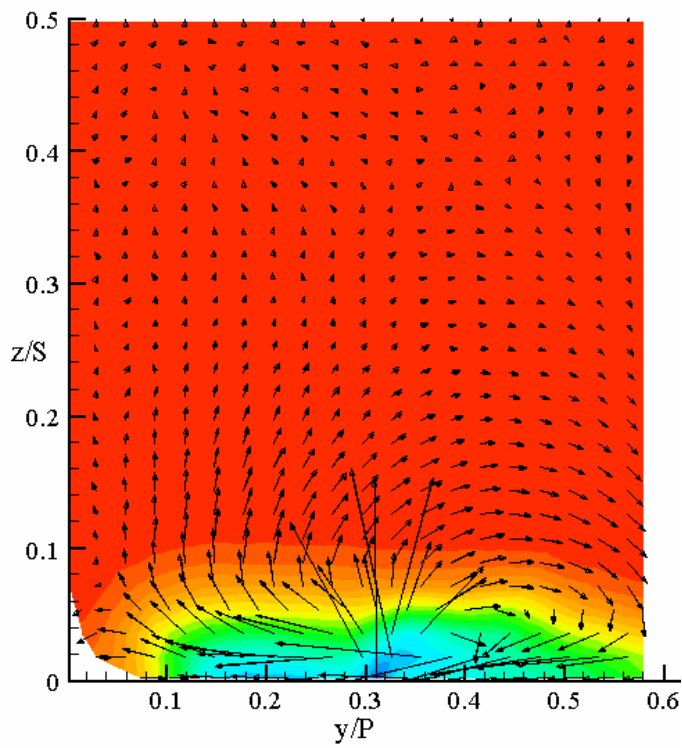


Figure D9. SS2 – PW6000.

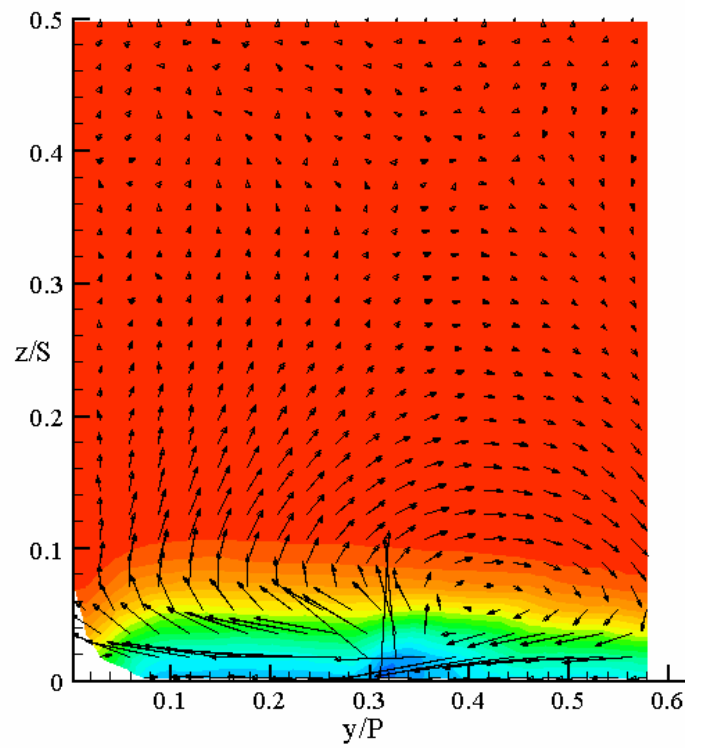


Figure D10. SS2 – PW4000.

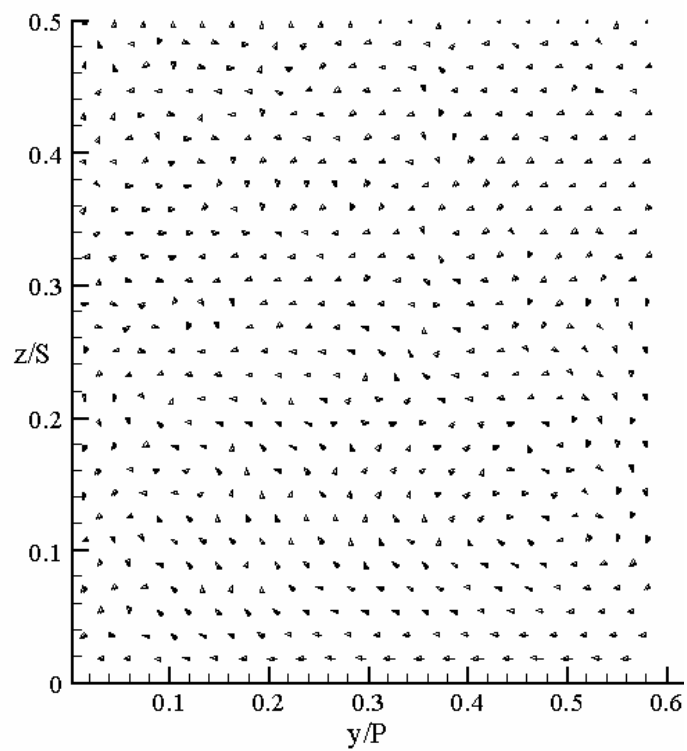


Figure D11. SS2 – Baseline (no fillet).

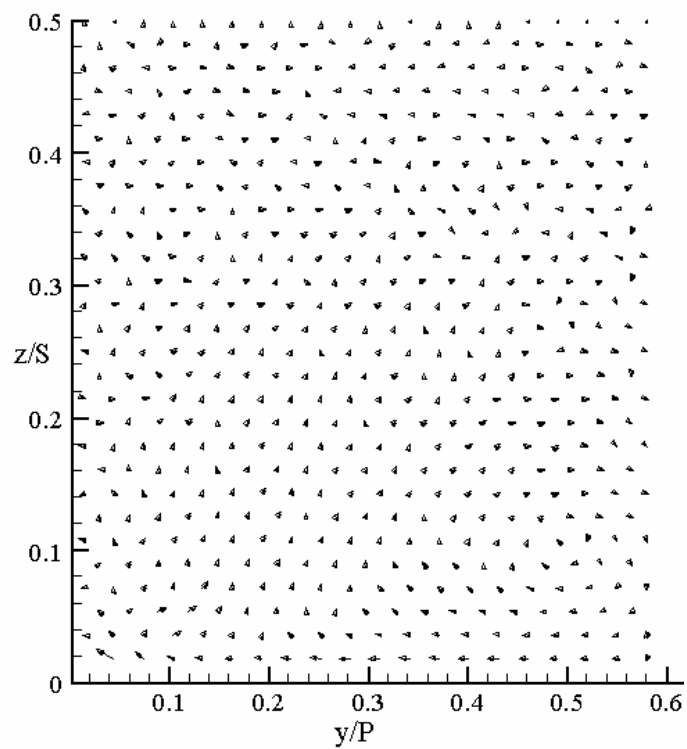


Figure D12. SS2 – Baseline (fillet).

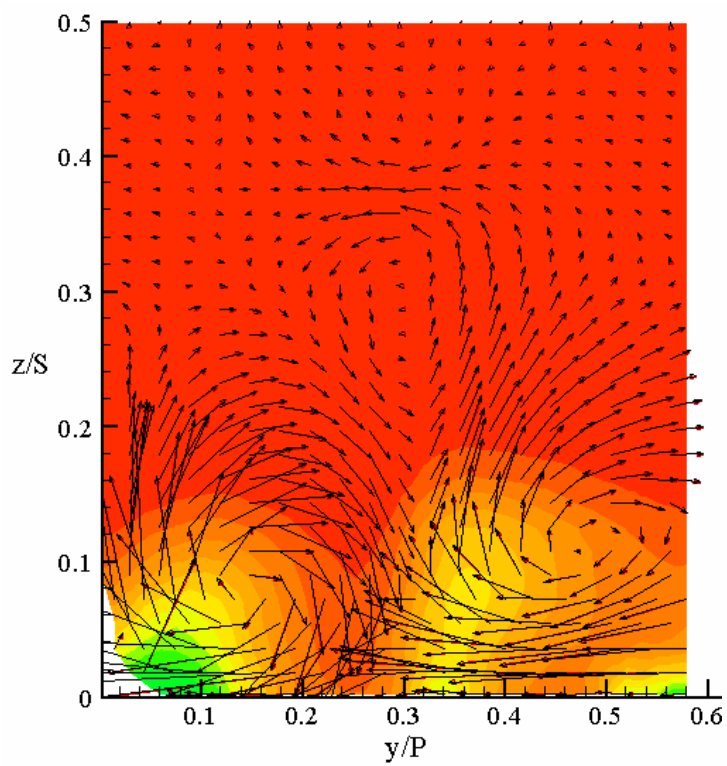


Figure D13. SS3 - ActiveMC.

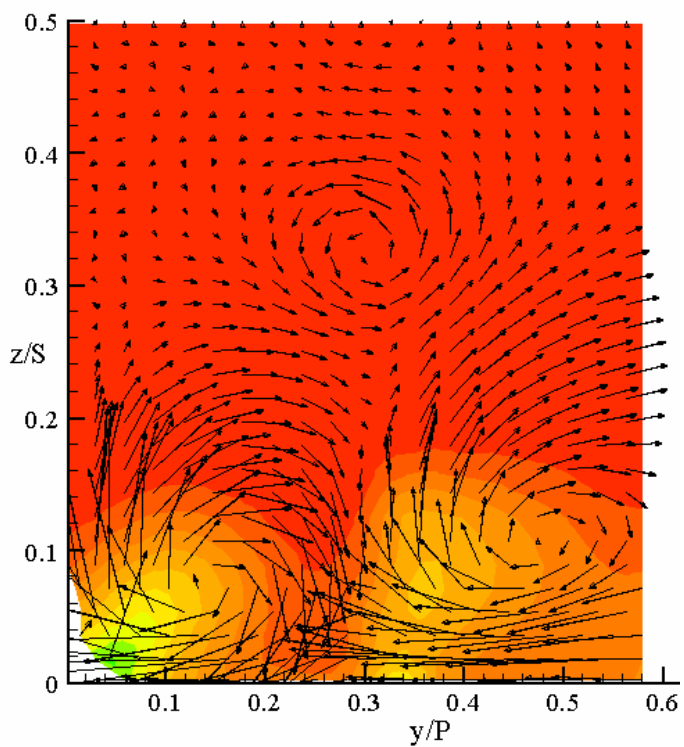


Figure D14. SS3 – ActiveMC
(no microcircuit).

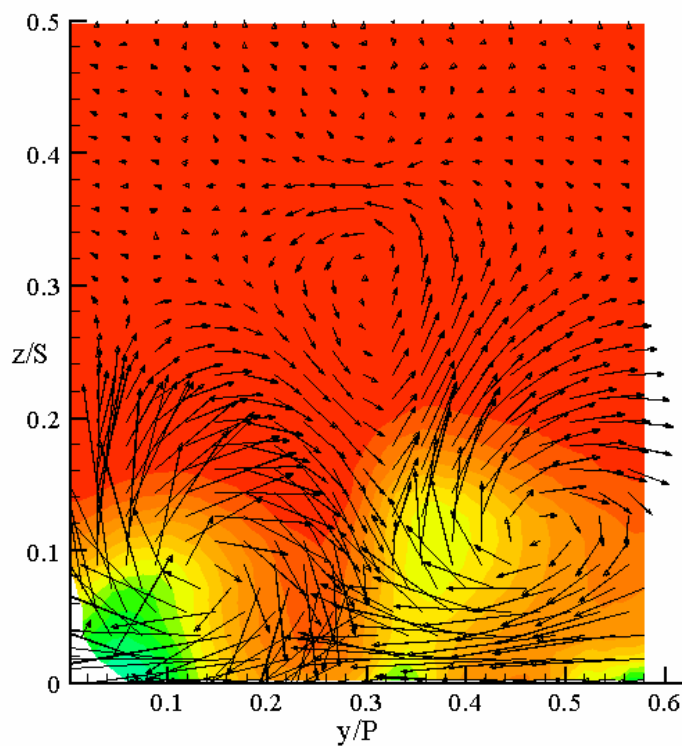


Figure D15. SS3 – PW6000.

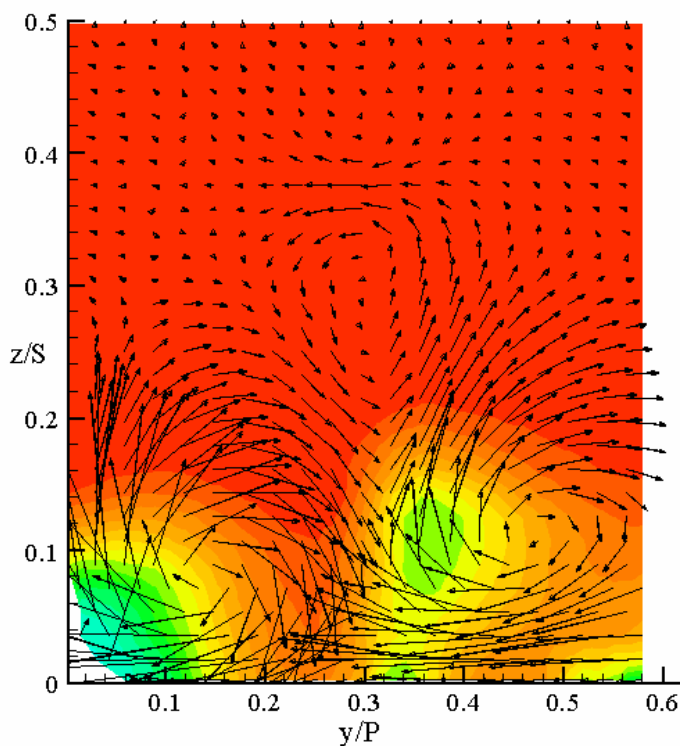


Figure D16. SS3 – PW4000.

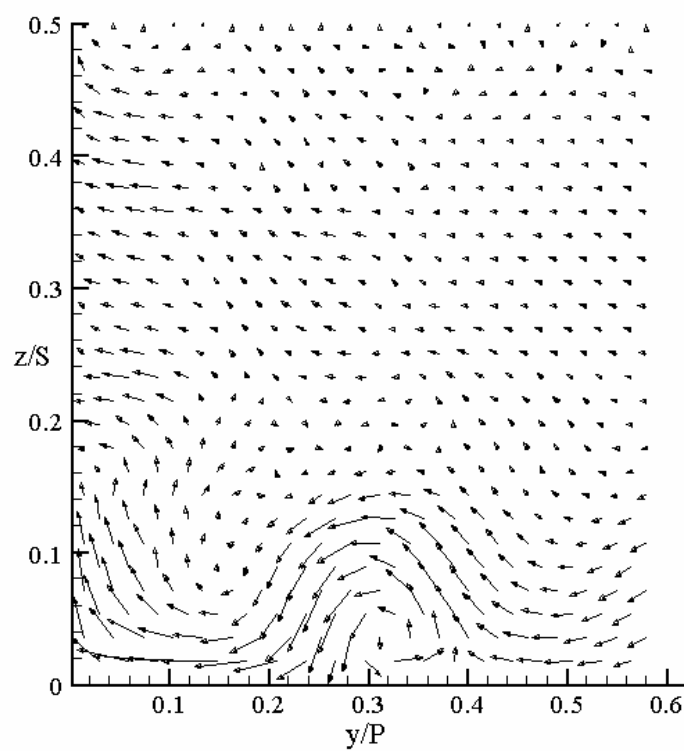


Figure D17. SS3 – Baseline (no fillet).

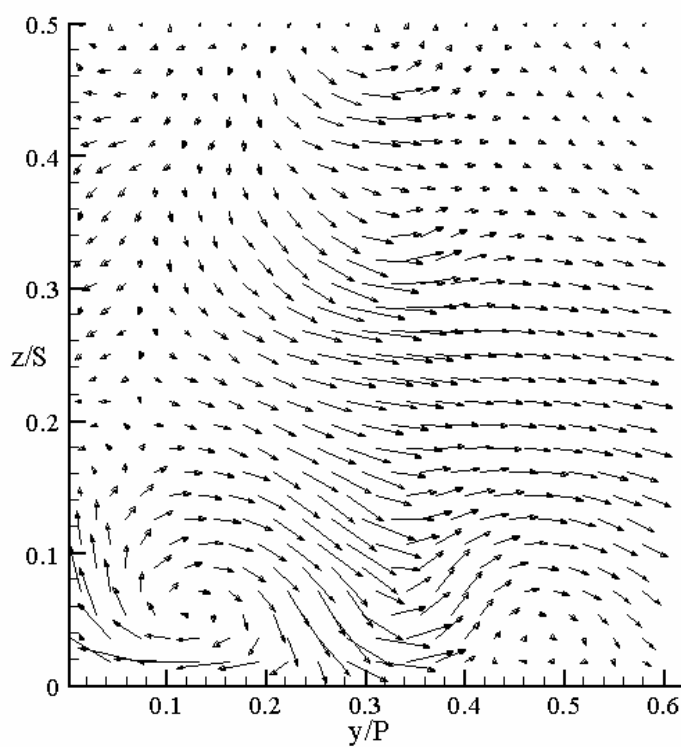


Figure D18. SS3 – Baseline (fillet).

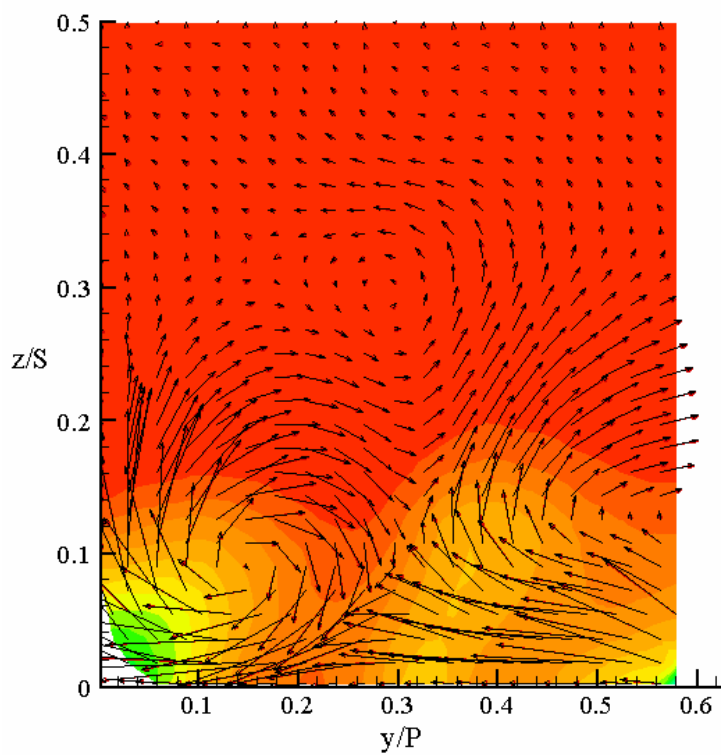


Figure D19. SS4 - ActiveMC.

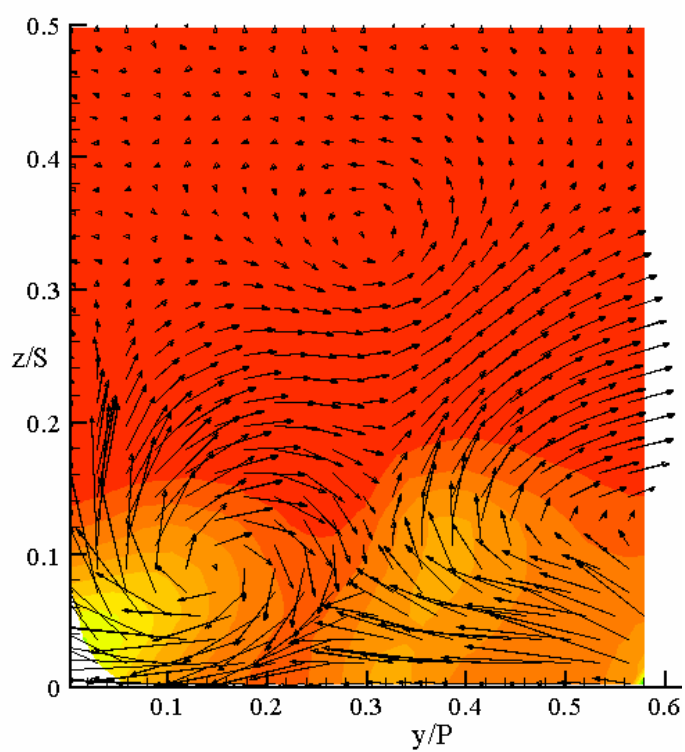


Figure D20. SS4 – ActiveMC
(no microcircuit).

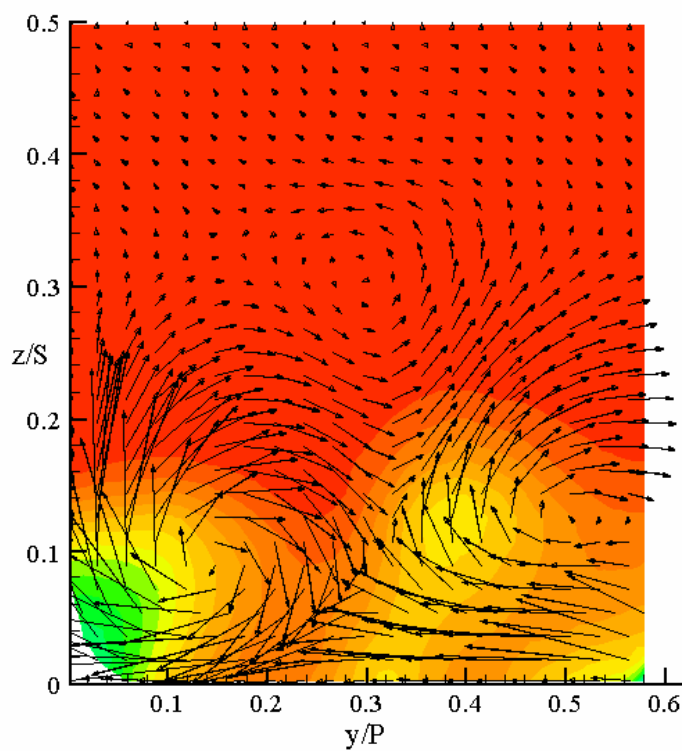


Figure D21. SS4 – PW6000.

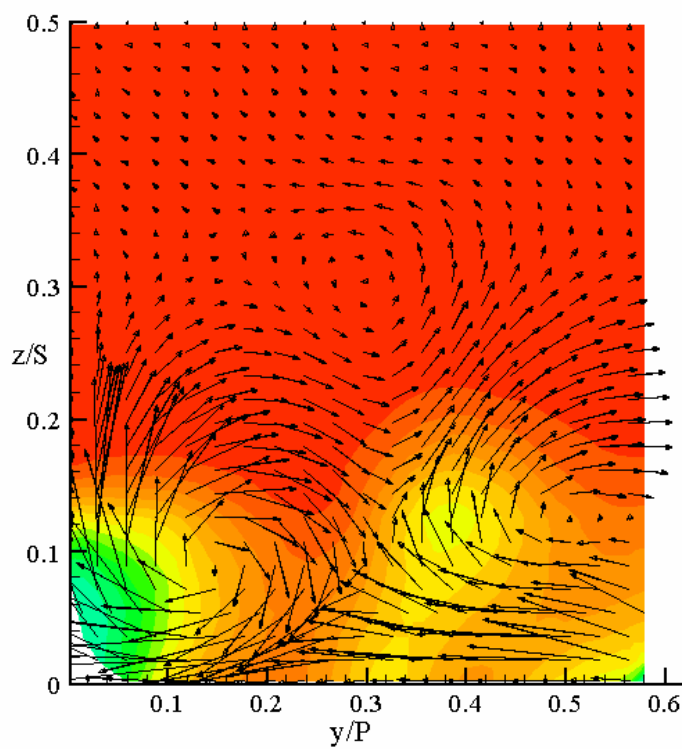


Figure D22. SS4 – PW4000.

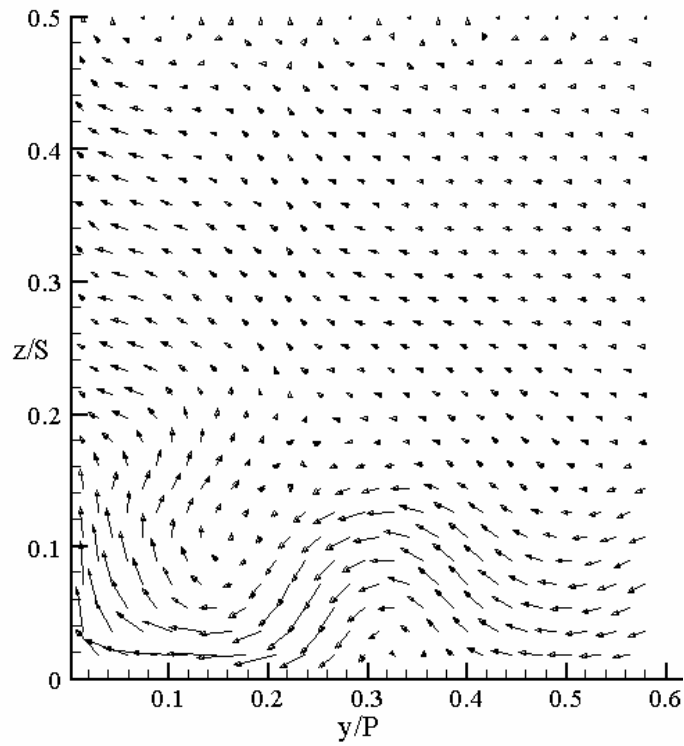


Figure D22. SS4 – Baseline (no fillet).

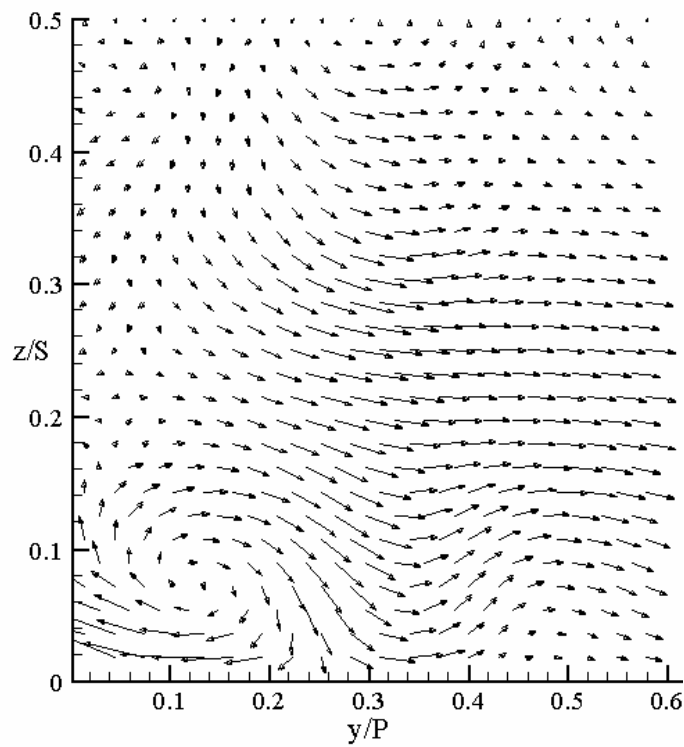


Figure D24. SS4 – Baseline (fillet).

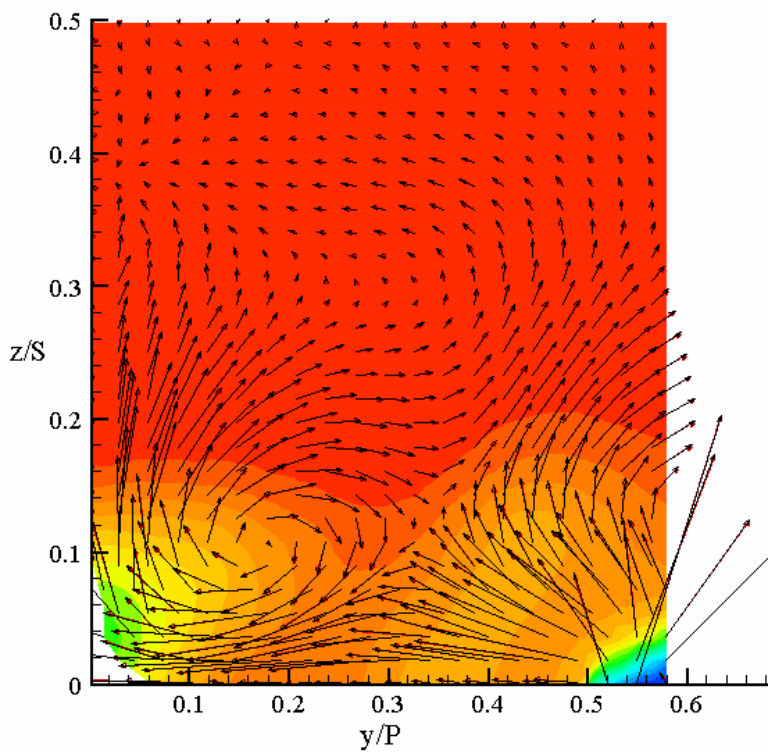


Figure D25. SS5 - ActiveMC.

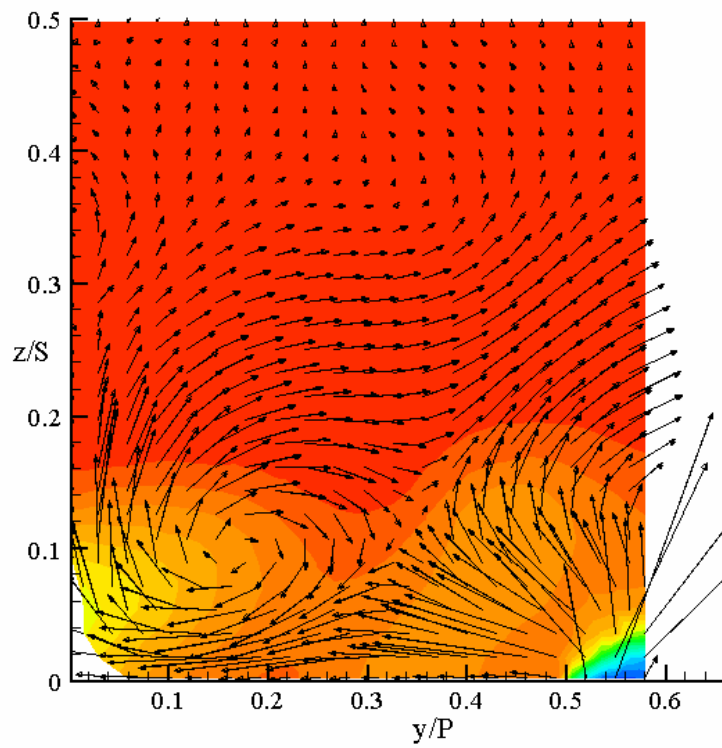


Figure D26. SS5 – ActiveMC
(no microcircuit).

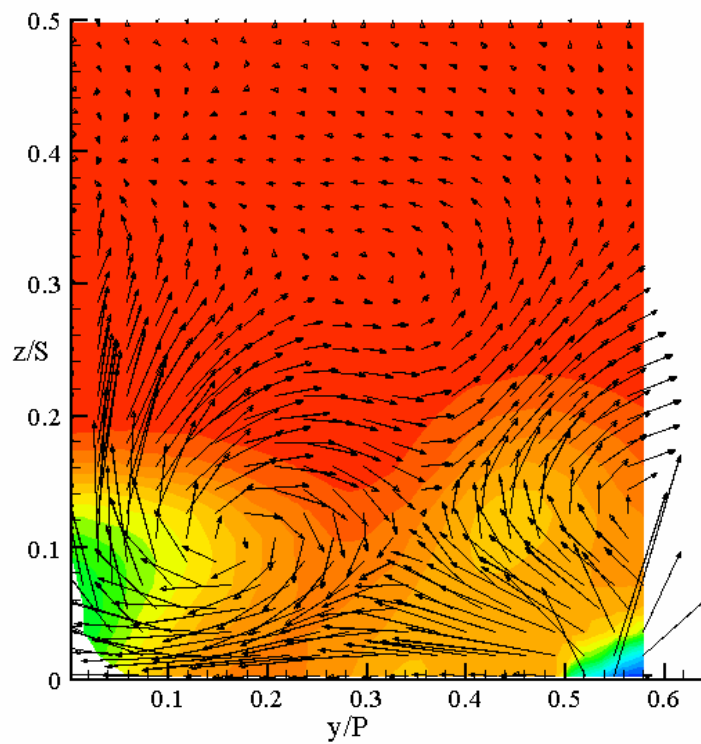


Figure D27. SS5 – PW6000.

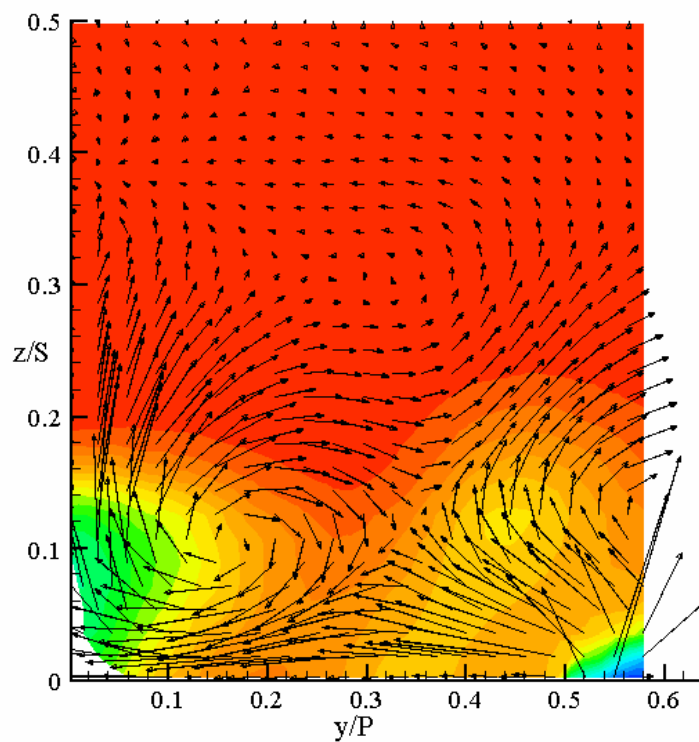


Figure D28. SS5 – PW4000.

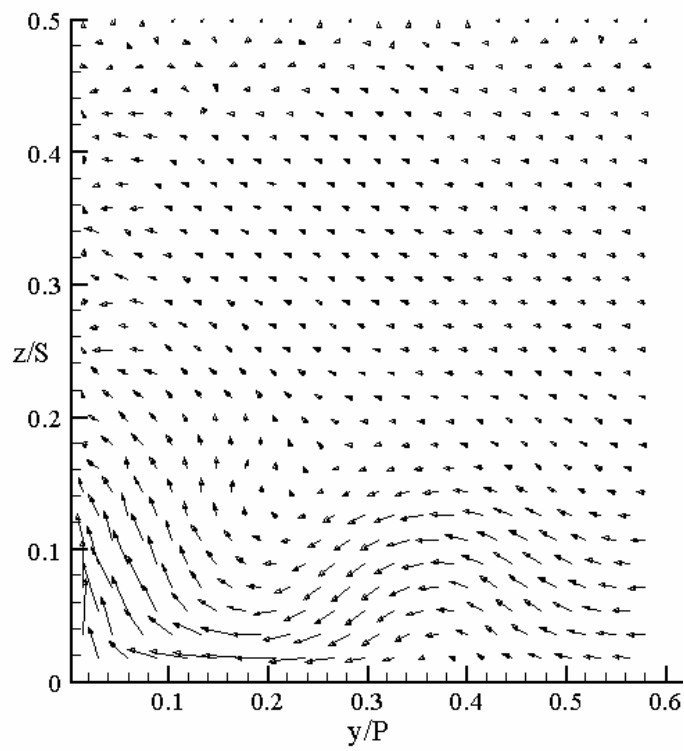


Figure D29. SS5 – Baseline (no fillet).

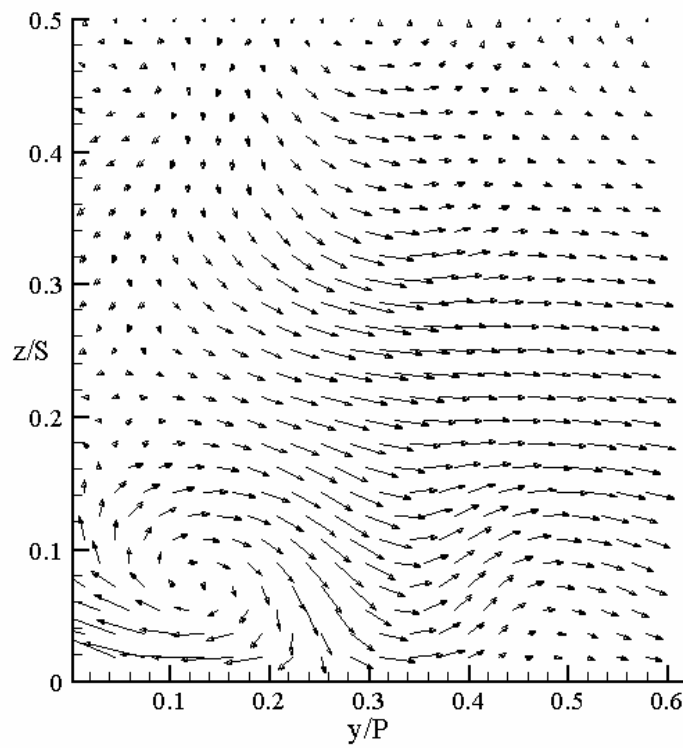


Figure D30. SS5 – Baseline (fillet).

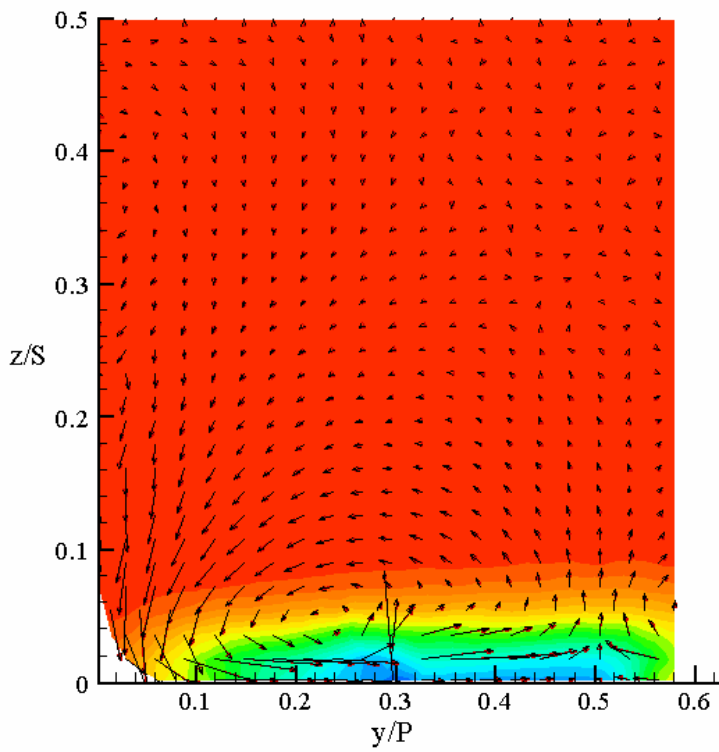


Figure D31. PS1 - ActiveMC.

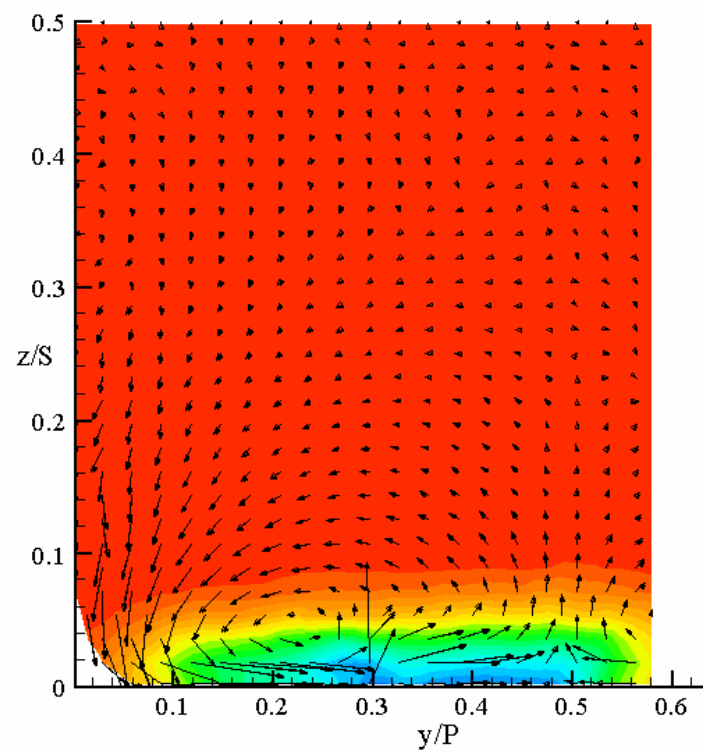


Figure D32. PS1 – ActiveMC
(no microcircuit).

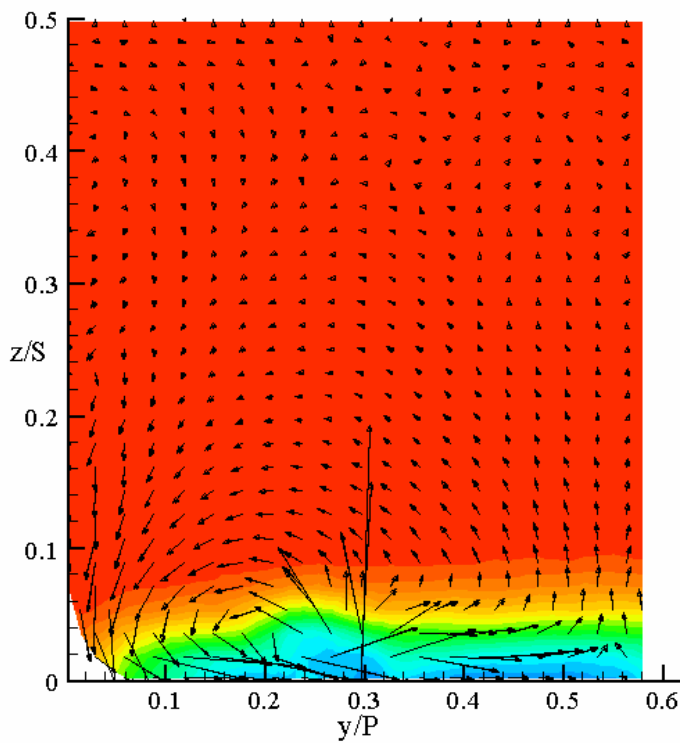


Figure D33. PS1 – PW6000.

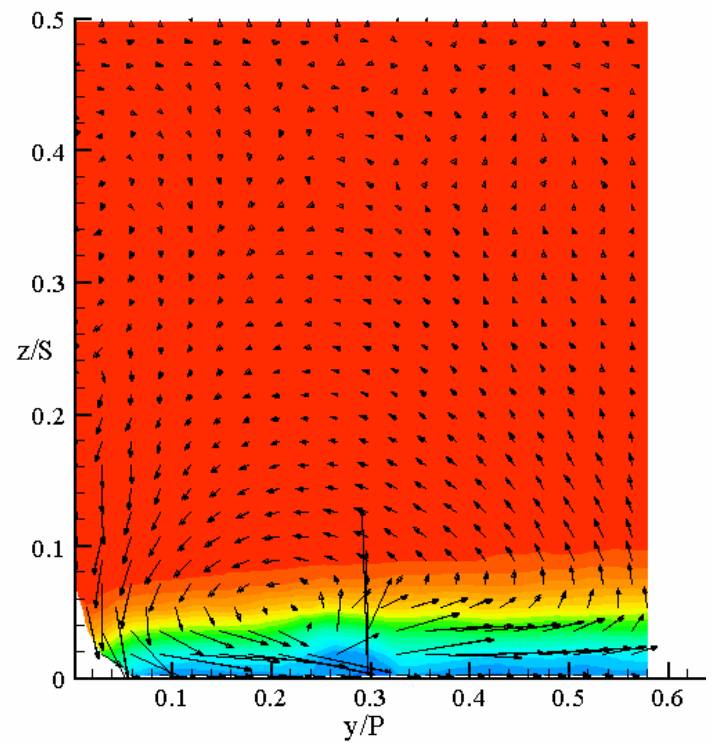


Figure D34. PS1 – PW4000.

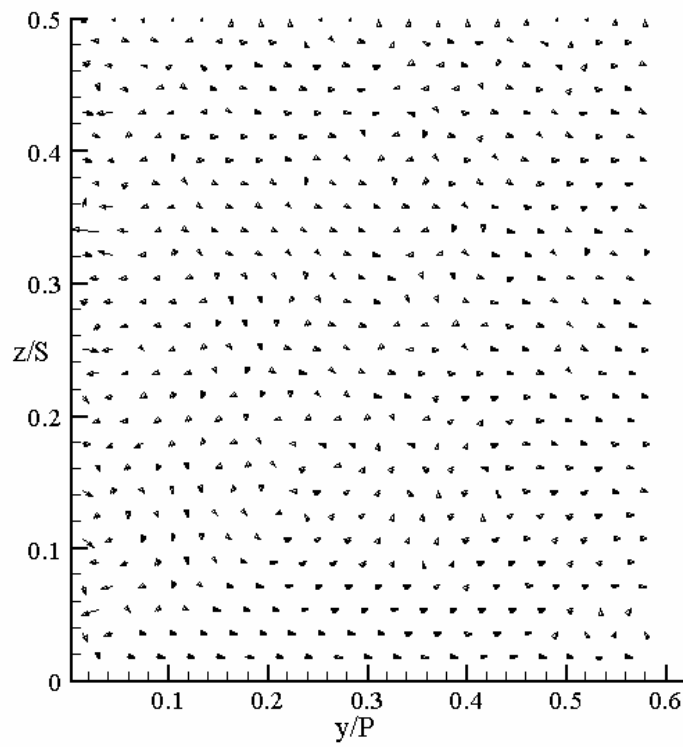


Figure D35. PS1 – Baseline (no fillet).

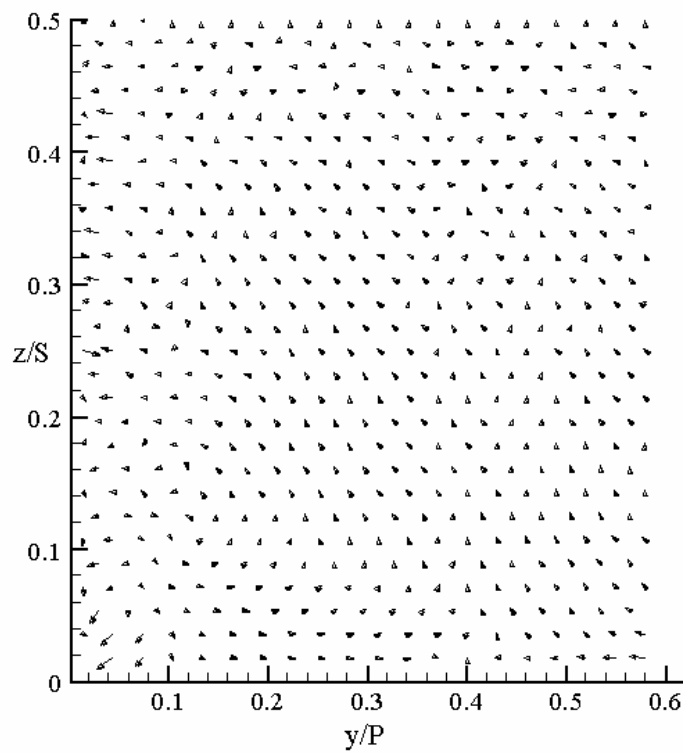


Figure D36. PS1 – Baseline (fillet).

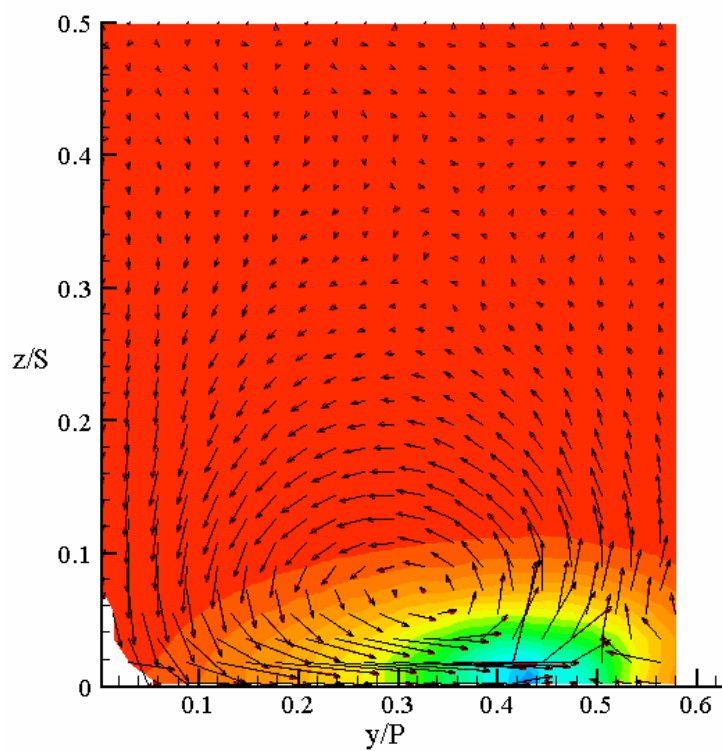


Figure D37. PS2 - ActiveMC.

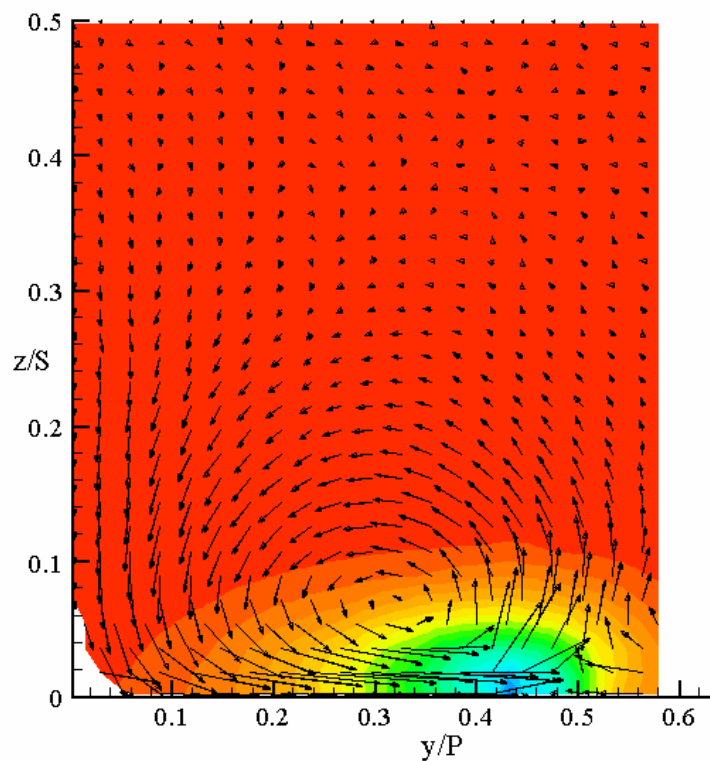


Figure D38. PS2 – ActiveMC
(no microcircuit).

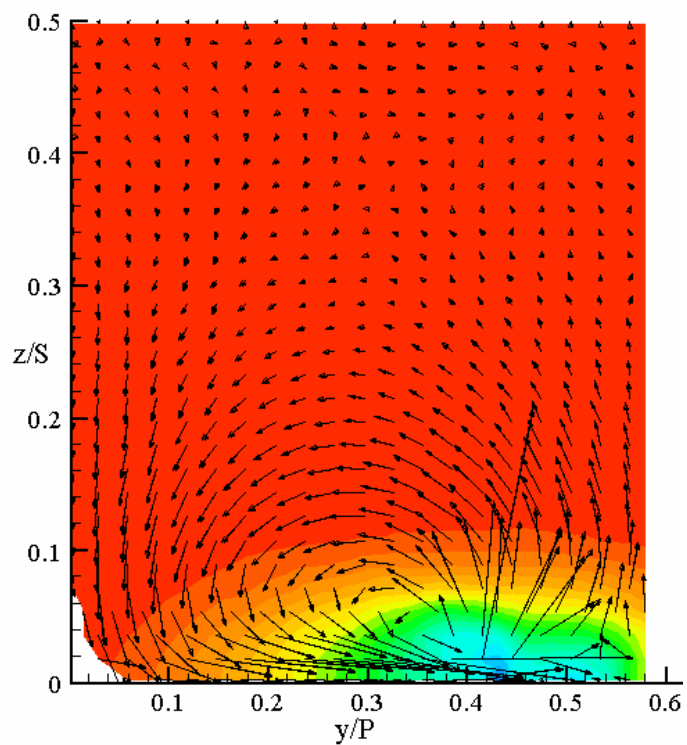


Figure D39. PS2 – PW6000.

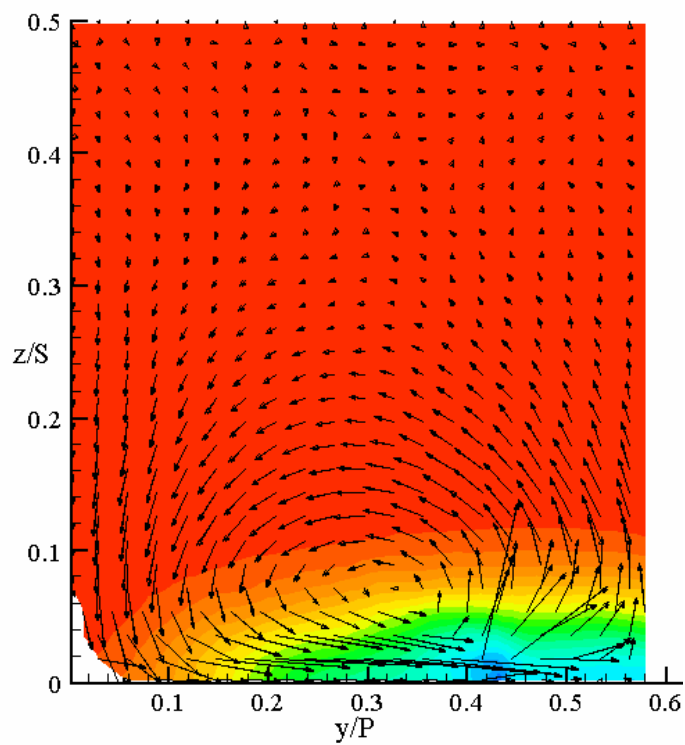


Figure D40. PS2 – PW4000.

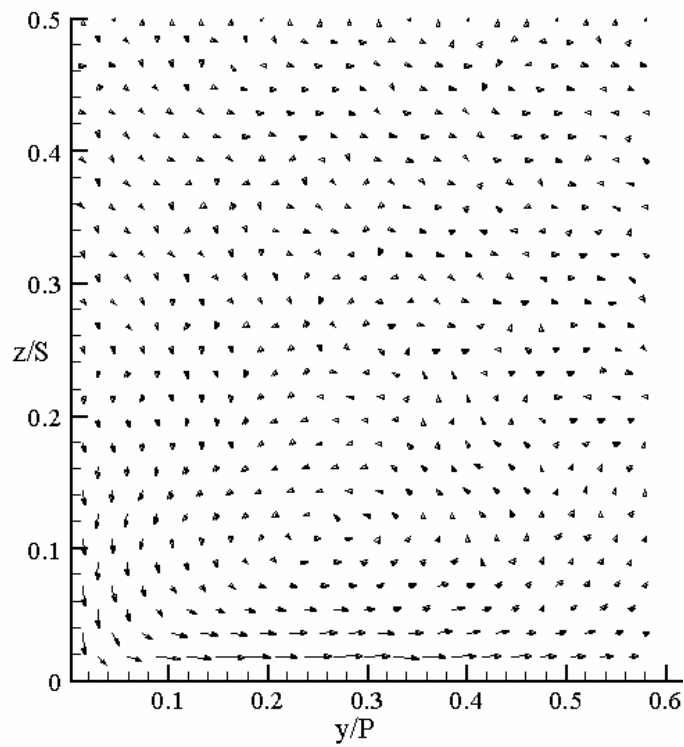


Figure D41. PS2 – Baseline (no fillet).

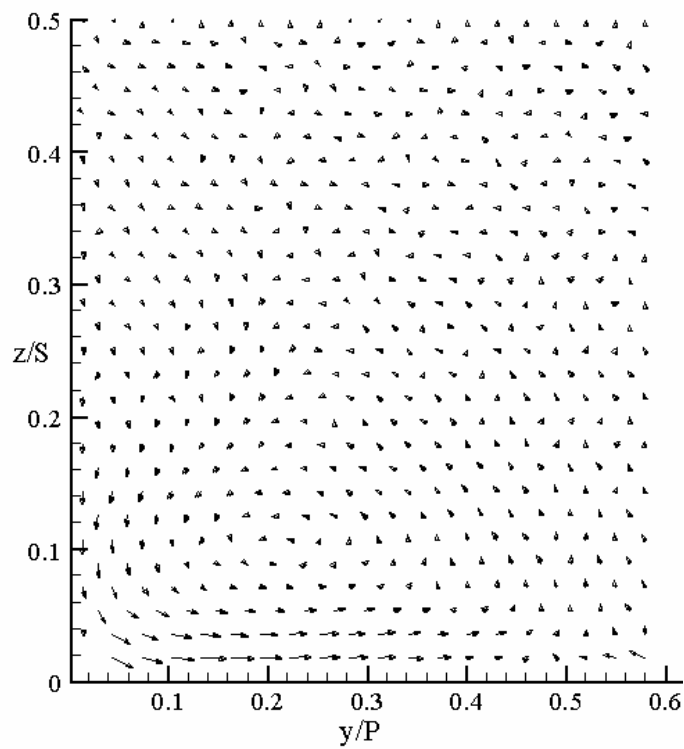


Figure D42. PS2 – Baseline (fillet).

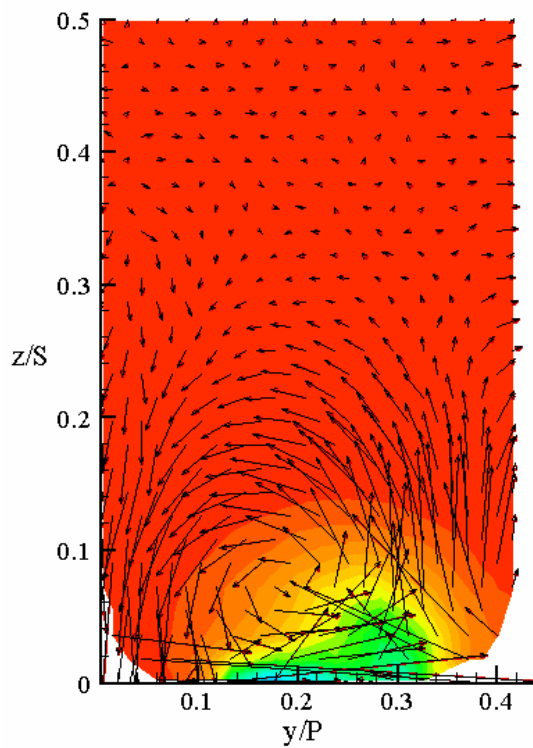


Figure D43. PS3 - ActiveMC.

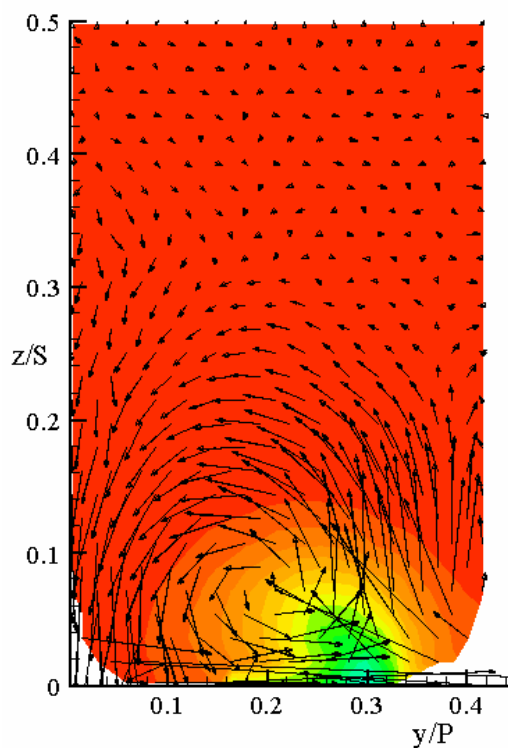


Figure D44. PS3 – ActiveMC
(no microcircuit).

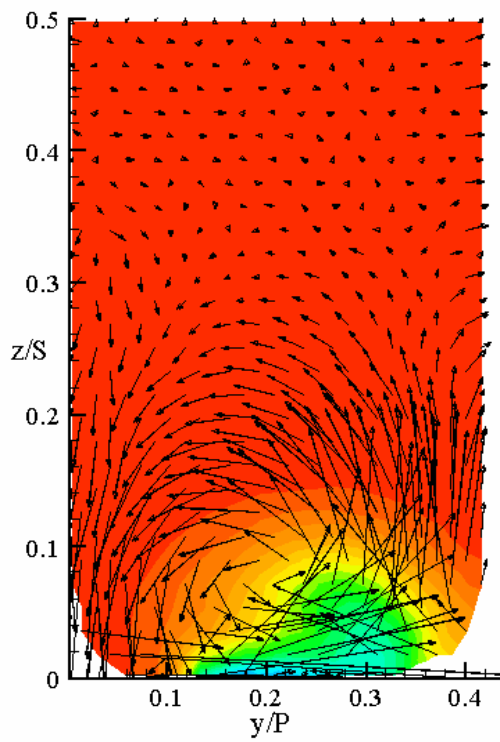


Figure D45. PS3 – PW6000.

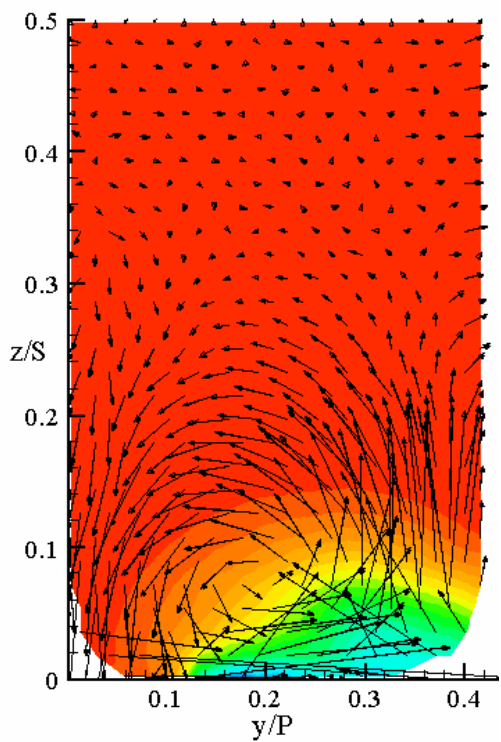


Figure D46. PS3 – PW4000.

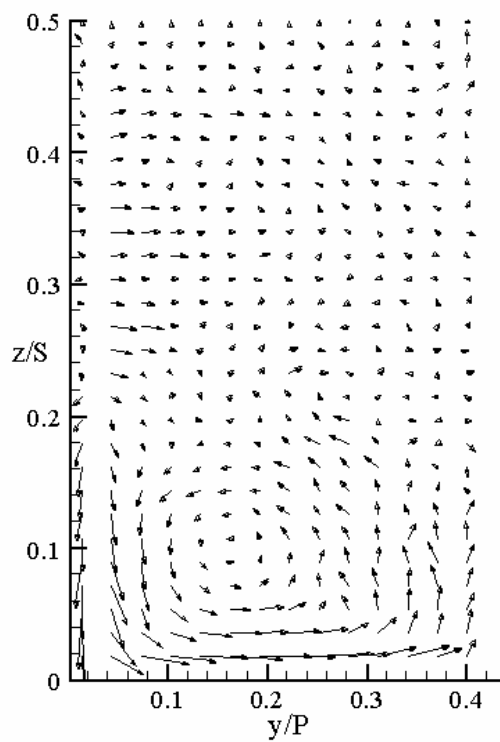


Figure D47. PS3 – Baseline (no fillet).

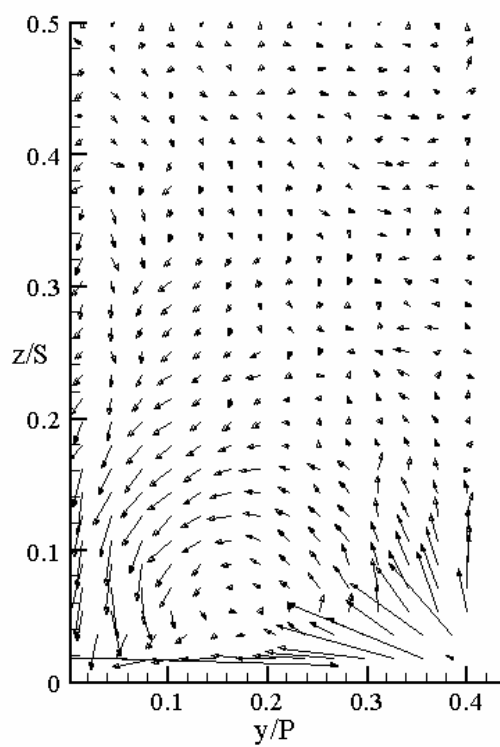


Figure D48. PS3 – Baseline (fillet).

ERIK MAX HOHLFELD

Erik Max Hohlfeld was born on December 5, 1979 in Olney, MD to H. Max Hohlfeld, Jr. and Carolyn A. Hohlfeld. After living in Germantown, MD until February 29, 1980, the family moved to Mt. Airy, MD where they continue to reside. At the age of four Erik attended Mt Airy Elementary School, followed by a stay at Mt Airy Middle School before moving on to South Carroll High School in Sykesville, MD. After graduating as valedictorian in 1997, Erik chose to attend Virginia Polytechnic Institute and State University. While at Virginia Tech, he participated in the CO-OP (cooperative education) program working a total of four semester at NIST (National Institute of Standards & Technology) in Gaithersburg, MD, for the Heat Transfer Group. Upon his graduation, in May 2002, with a Bachelor of Science in Mechanical Engineering, he officially enrolled in graduate school. In May 2003, Erik received his Master of Science in Mechanical Engineering with future plans to begin a career in the field of Mechanical Engineering.

A few other important things to know include his favorite....

University/College	Virginia Tech Hokies
Professional Football	Washington Redskins
NASCAR	Sterling Marlin in the Coors Light Dodge
Truck	Dodge (Ram and Dakota)
Sports Car	Dodge Viper

ERIK MAX HOHLFELD

EDUCATION:

Virginia Polytechnic Institute and State University, Blacksburg, VA
M.S. Mechanical Engineering, Cum Laude, 2003
Focusing in Heat Transfer and Fluid Mechanics

Virginia Polytechnic Institute and State University, Blacksburg, VA
B.S. Mechanical Engineering, Cum Laude, 2002

South Carroll High School, Sykesville, MD
High School Diploma, Valedictorian, 1997

ENGINEERING WORK EXPERIENCE:

Virginia Tech Experimental & Computational Convection Laboratory (VTECCCL), Blacksburg, VA
Graduate Research Assistant, 1/2002 – 5/2003

Study film cooling through computational modeling and experimental work
Explore various flow phenomena within a turbine cascade
Analyze and evaluate various cooling methods for turbine blades

National Institute of Standards & Technology (NIST), Gaithersburg, MD
CO-OP, Heat Transfer Group - Building & Fire Research Laboratory, 5/1999 – 8/2001
Development of reference materials, Infrared photography
Conduct thermal conductivity & moisture measurements
Design, model, test & validate experimental equipment

Center for Power Electronics Systems (CPES), Virginia Tech, Blacksburg, VA
Undergraduate Research Assistant, 1/2001 - 5/2001
Analyze & create models for power electronics cooling (CFD and FEA)
Validate computer models via experiment

ACTIVITIES & HONORS:

Engineer in Training (passed EIT)	2002	Pi Tau Sigma (M.E. Honors)	2001-2003
Deans List	1998-2002	Kappa Theta Epsilon (Co-op Honors)	1999-2001
A.S.M.E.	2001-2003	Tau Beta Pi (Engr. Honors)	2001-2002
University Honors Associates	1997-1998	University Honors Program	1997-1998
South Carroll H.S. Valedictorian	1997	Who's Who of American H.S. Students	1995-1997
Hiking, Biking, Camping, Gardening		Hokie Fan	

CURRENT PUBLICATIONS:

Hohlfeld, E., Christophel, J., Couch, E. and Thole, K. A., "Predictions of Cooling from Dirt Purge Holes Along the Tip of a Turbine Blade," under review for the 2003 International Gas Turbine and Aero-engine Congress and Exposition and *Journal of Turbomachinery*.