MODELING THE FORMATION OF VOLCANIC SMOKE RINGS

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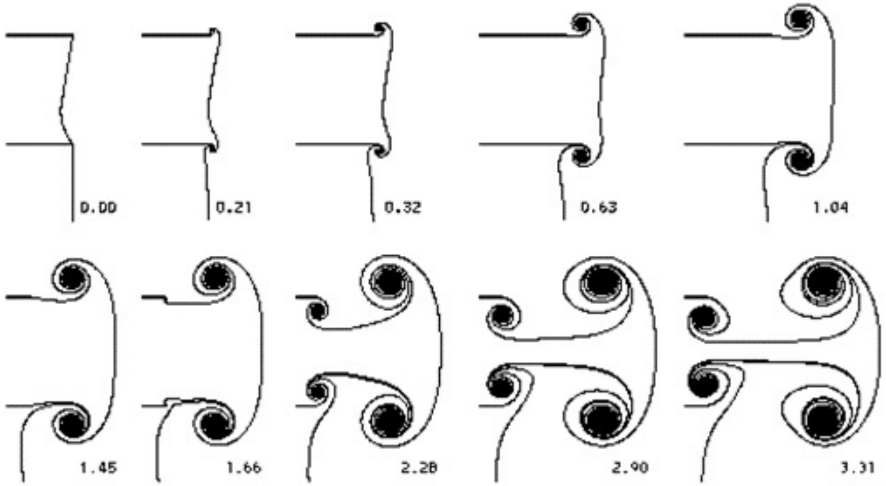
Agenda

- Vortex rings
- Previous studies
- Volcano smoke rings
- Model
- Results
- Conclusions

Vortex rings

Torus-shaped vortex in a fluid or gas.

Vortex rings form when a mass of fluid is impulsively pushed from an enclosed space through a narrow opening

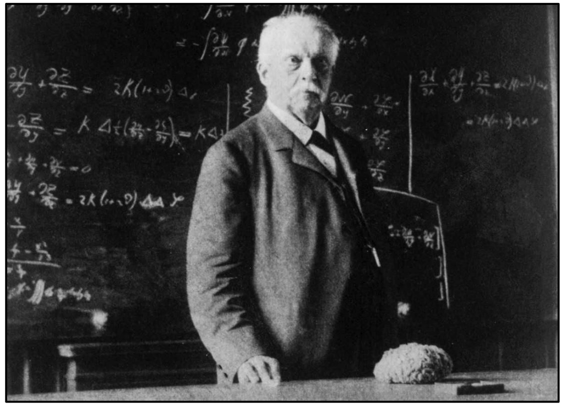


James and Madnia 1996

Examples of vortex rings

Previous studies

Vortex rings have been observed since 17th century and studied for more than a century…



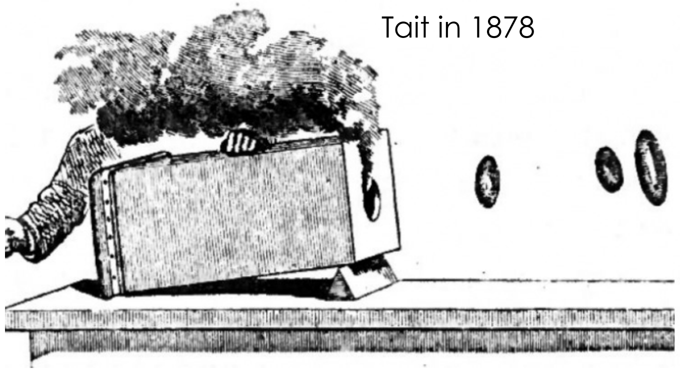
Hermann von Helmholtz, described the three-dimensional motion of ideal fluid in the vicinity of vortex filaments (1858).

$$\Gamma = \int_A \vec{\omega}\cdot\vec{n}dA = \oint_c \vec{u}\cdot d\vec{s}$$

$$\frac{D\Gamma}{Dt} = 0$$

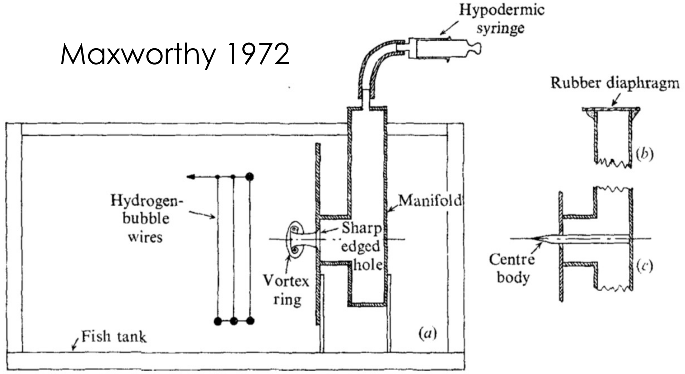
circulation

Tait in 1878



First experiments to verify Helmholtz theoretical predictions..

Maxworthy 1972



Stability of laminar vortex rings

Saffman studied viscous diffusion effects on rings with small cross section(1970)

$$U = \frac{\varkappa}{4\pi R}\left\{\log\frac{8R}{\sqrt{4\nu t}} - 0.558 + O\left[\left(\frac{\nu t}{R^2}\right)^{1/2}\log\frac{\nu t}{R^2}\right]\right\}$$

The effect of viscosity is to slow down the ring as -logvt

And many other studies…

1979: Circulation as a function of nozzle properties (Didden)

1988: Parameters for transition from laminar to turbulent (Glezer)

1994-1996: Numerical approaches (Nitsche&Kransky, James and Madnia).

2000-2018: Pinch-off problem is analysed (Shusser&Gharib, Danaila&Luddens)

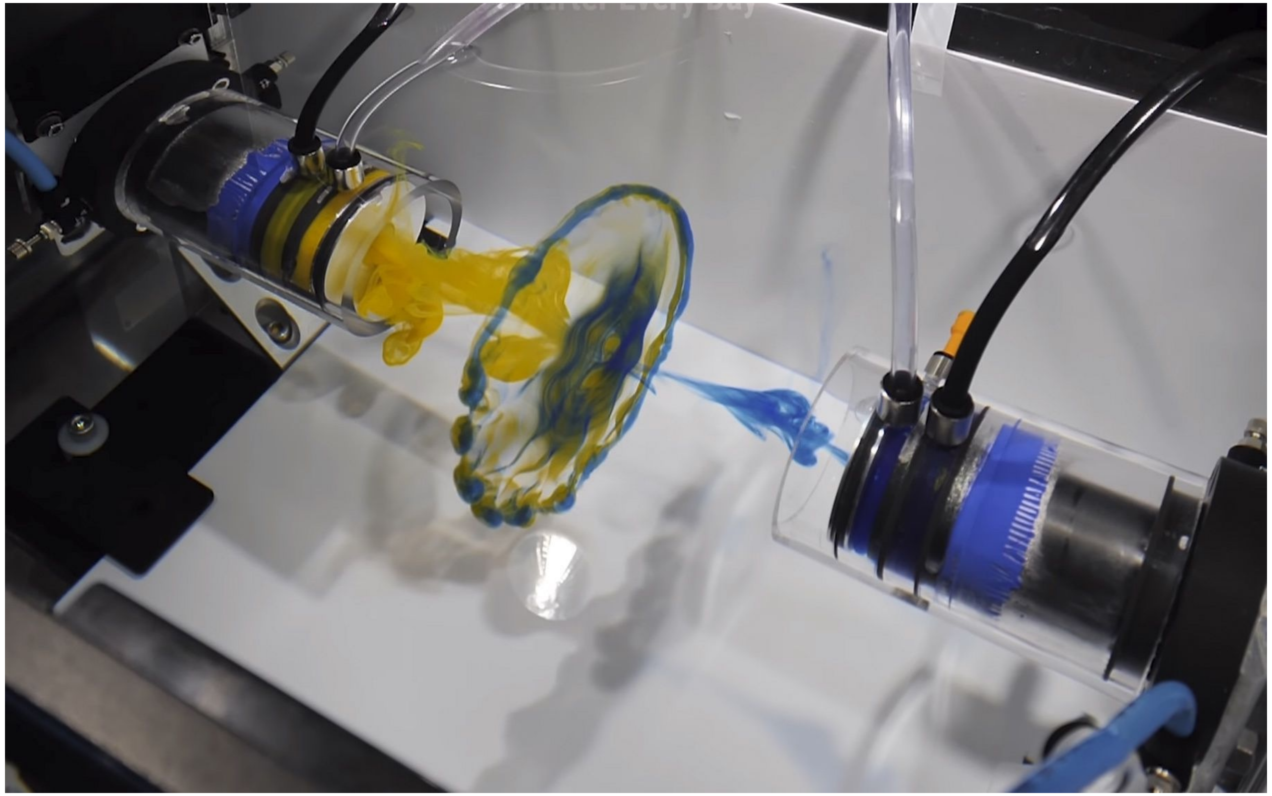
So we know that…

Important aspects are:

- Impulse type
- Size and shape of the opening
- Characteristics of the fluids
- Diffusion and convection are driving processes

According to the above we can calculate…

- Rings velocity and circulation
- Ring appearance and starting diameter
- Rings life and diameter change



Credit:DIY photography

And volcanoes too!

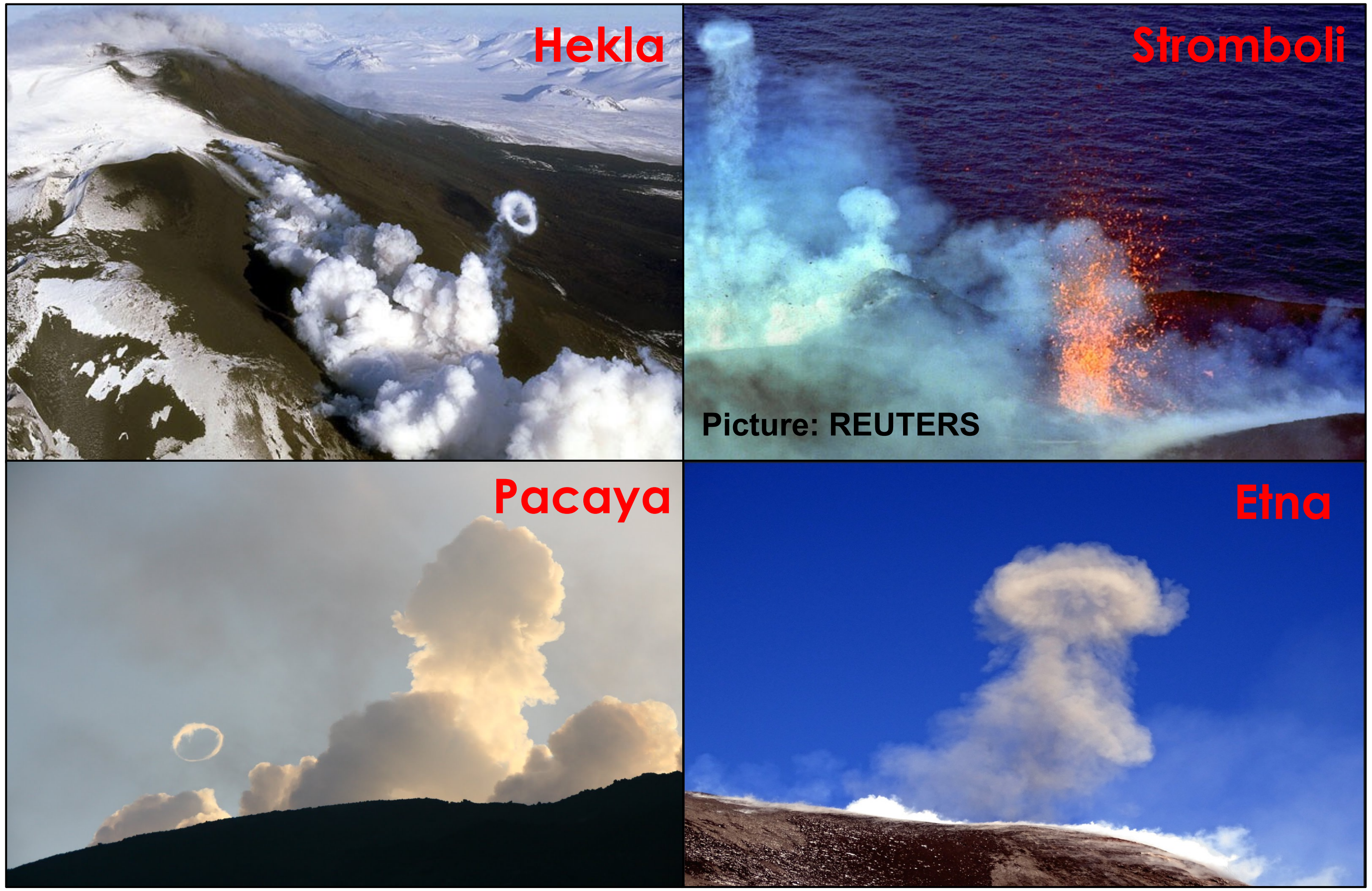
First observations

Rings of volcanic ash

	Vesuvius		Etna
1724	Ignazio Sorrentino		
1725	Ignazio Sorrentino		
1733	Ignazio Sorrentino		
1755	Giovanni Ma. della Torre		
1761	Gaetano de Bottis		
		1763	Giuseppe Recupero
1775	Gaetano de Bottis		
1819	Carlos de Gimbernat	1819	Stephano Moricand
1828	Charles Babbage		
		1842	Leopoldo del Re
1845	Ernesto Capocci		
1878	Werner Siemens		

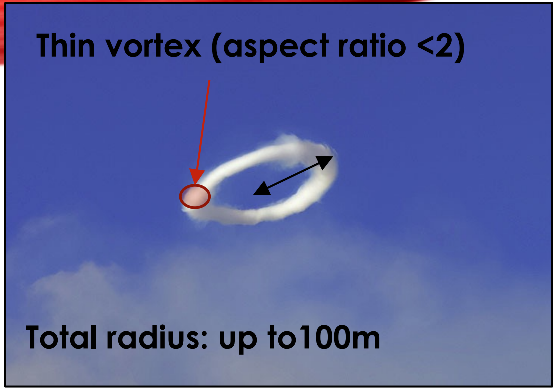
ALASKA
Mount Redoubt
ITALY
Mount Etna and Stromboli
ICELAND
Eyjafjallajökull and Hekla
ECUADOR
Tungurahua
GUATEMALA
Pacaya,
JAPAN
Mount Aso
INDONESIA
Gunung Slamet and Batu Tara
NEW ZELAND
Whakaari
NICARAGUA
Momotombo

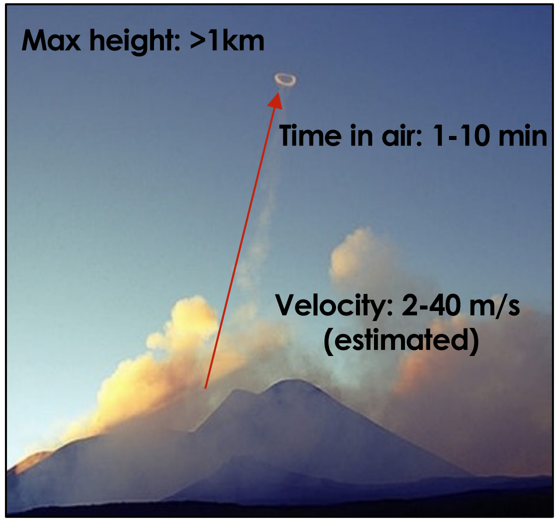
Examples of volcanic smoke rings

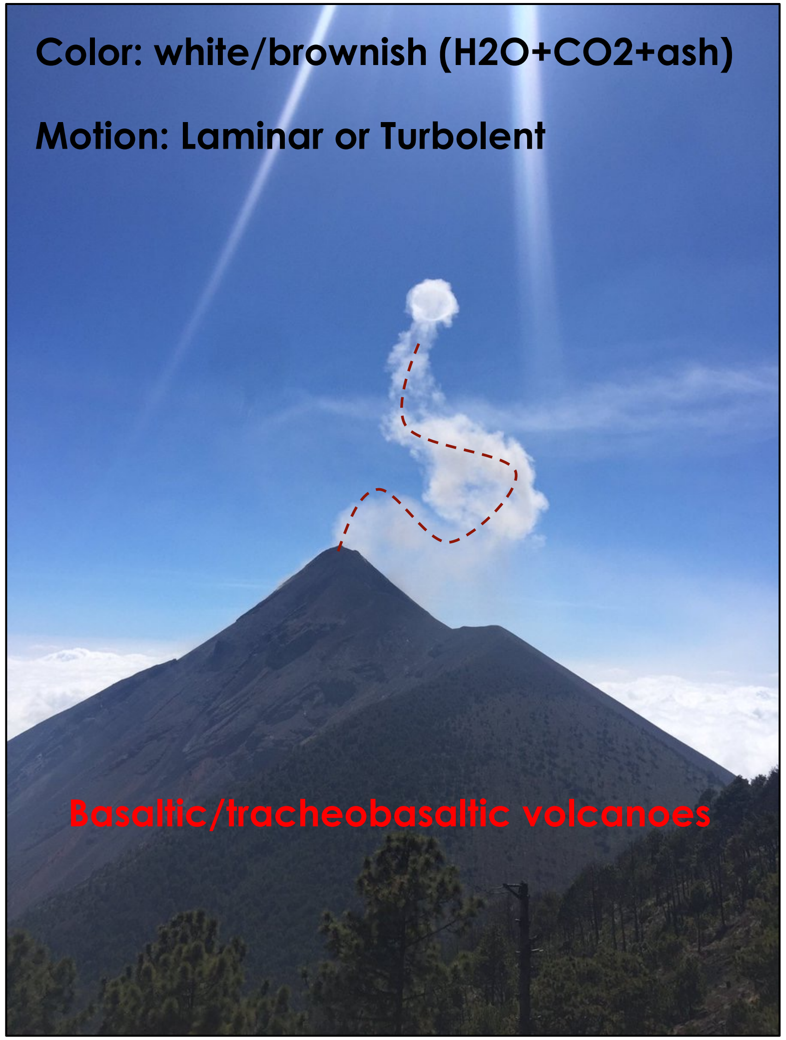


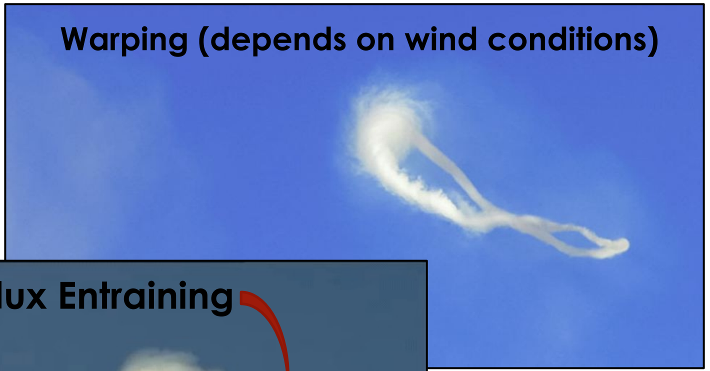
Picture Credit. Top left: REUTERS; Top right: swisseduc.ch; Bottom Left:skagwaydelta; Bottom right: Boris Benhcke (INGV)

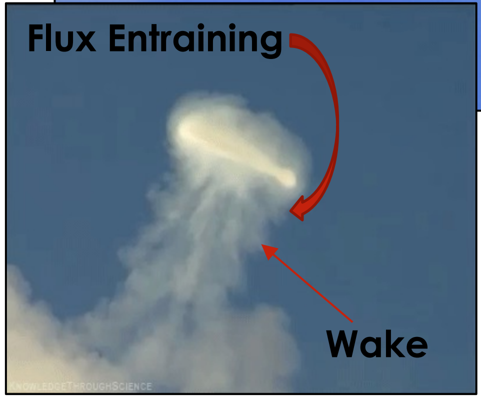
Observables

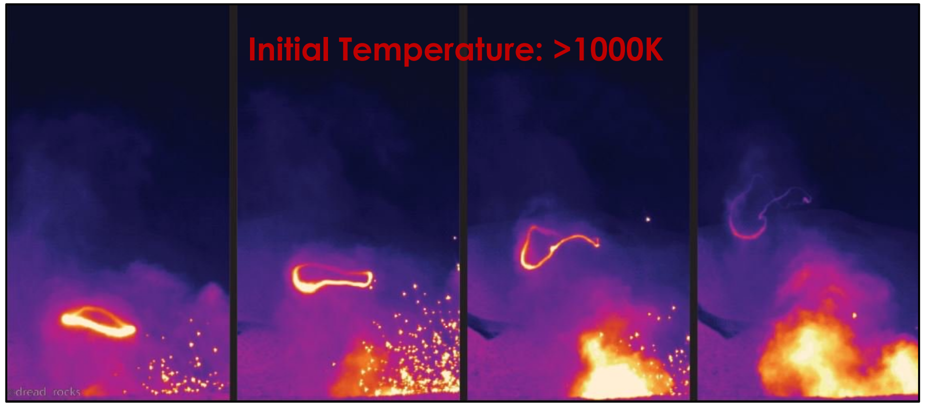






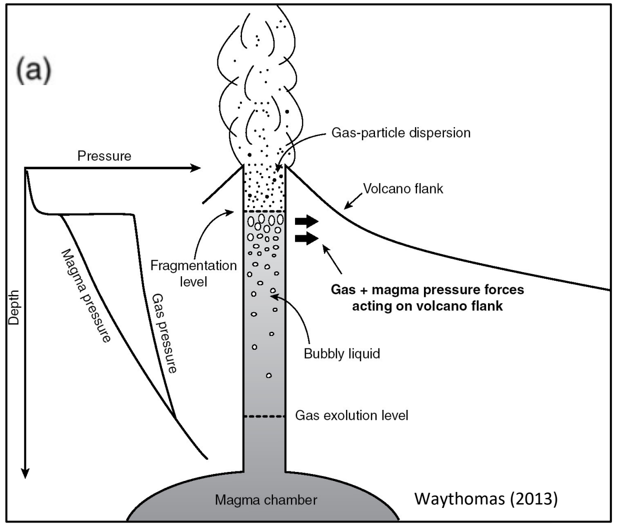






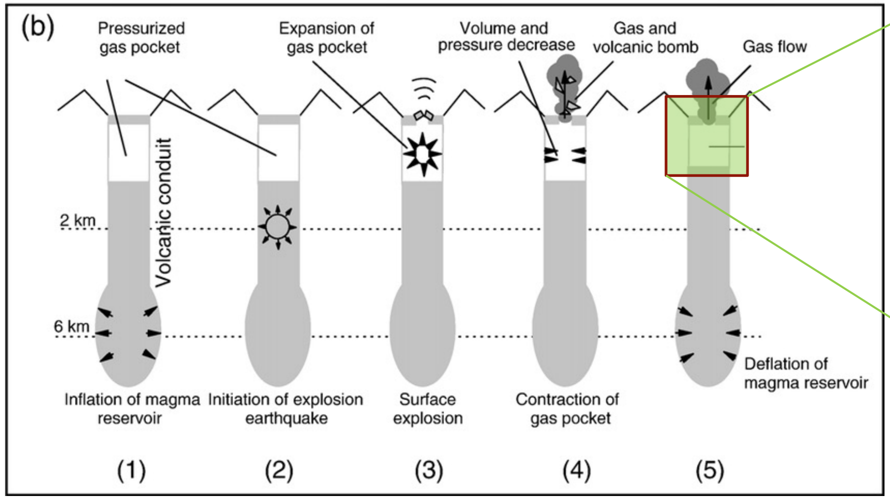
From observables we can get information on the dynamics processes

Possible dynamics



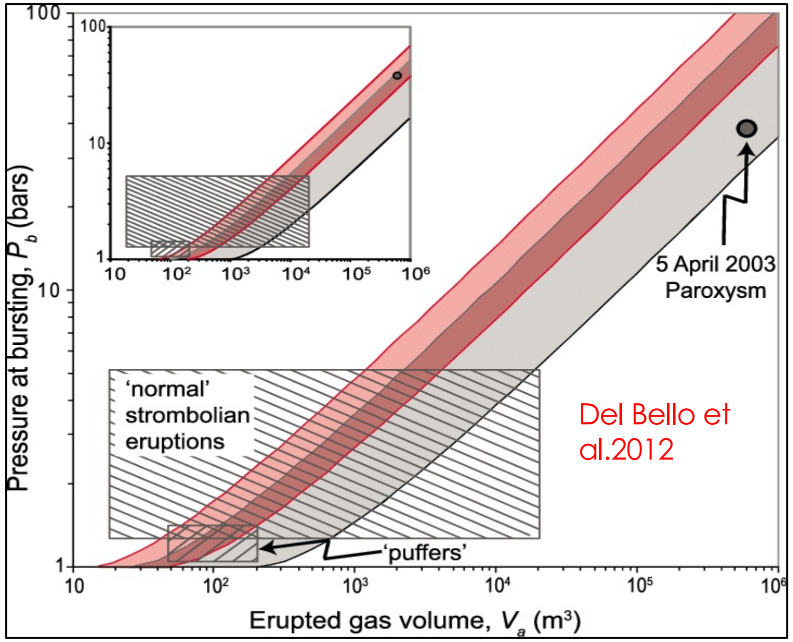
a) Open conduit with free degassing

b) Closed conduit with lava dome



Puffer

Modified from Maryanto (2008)



Del Bello et al.2012

In order to match the observations….

1) What's the necessary impulse amplitude and duration?
2) How do conduit radius and vent shape influence the ring shape?
3) How do thermal properties affect ring formation and permanence?

Numerical Simulations can help to answer these questions

Model

Time-dependent Non-isothermal multiphysics model

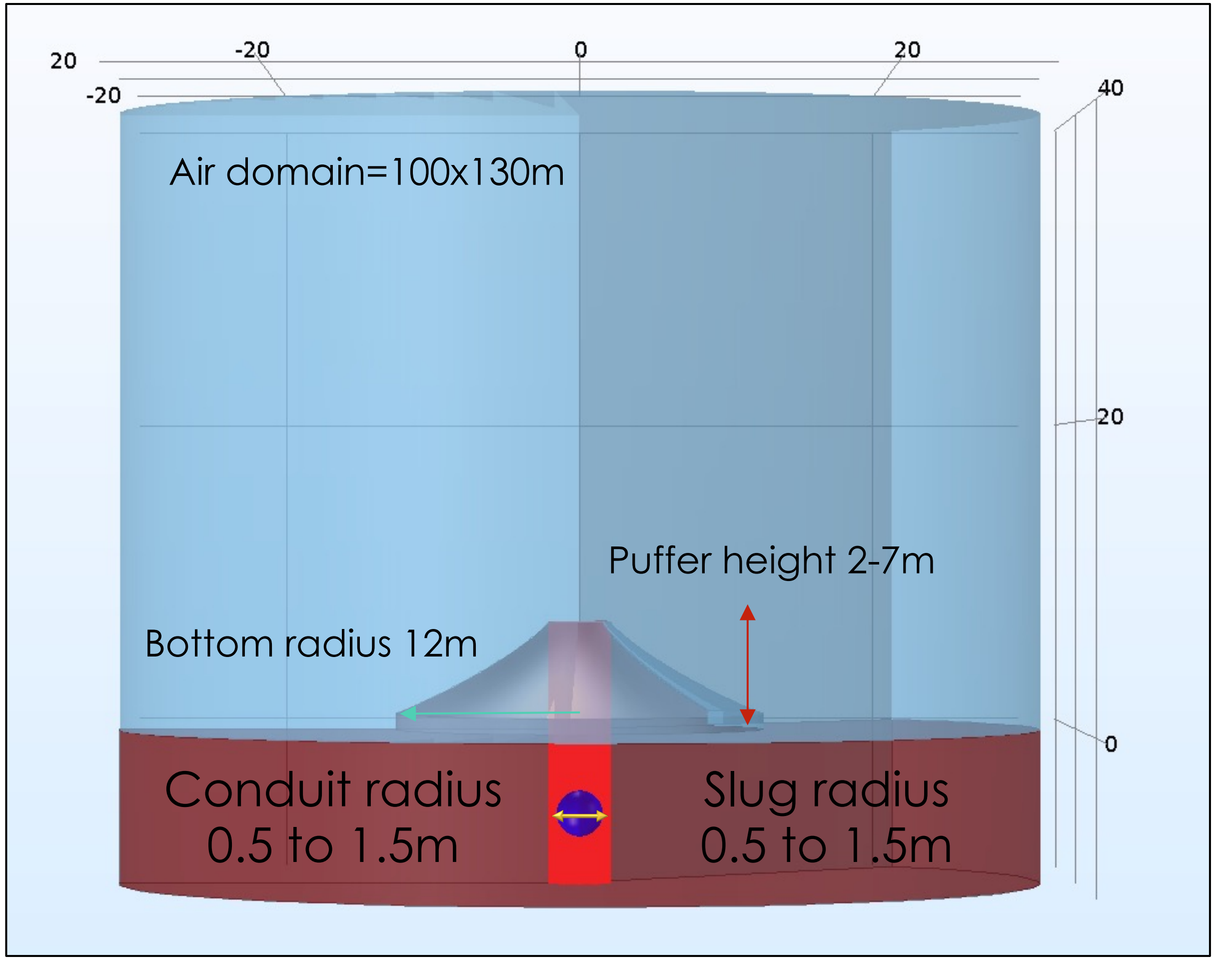
Fluid Flow
Reynolds averaged Navier Stokes (turbulent k-ω)

Heat Transfer
Turbulent(Prandtl=0.8) with natural convection

Transport of diluted species
Diffusion

Parameters	Air	Steam	Magma
T_0[K]	283.15	1073.15	1373.15K
P_0[Pa]	1e5	1e5	1e5
Density[kg/m³]	1.2	0.2	2000
Dynamic viscosity[Pa*s]	1.7e-5	4e-5	5e4

2D axi-symmetric revolved geometry



Slug explosion=overpressure (1kPa,10kPa, 100kPa)

Model equations

Reynolds averaged Navier Stokes (turbulent k-ω)

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} =$$

$$\nabla\cdot\left[-p\mathbf{I} + (\mu+\mu_T)\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right] + \mathbf{F}$$

$$\rho\nabla\cdot(\mathbf{u}) = 0$$

$$\rho\frac{\partial k}{\partial t} + \rho(\mathbf{u}\cdot\nabla)k = \nabla\cdot\left[(\mu+\mu_T\sigma_k^*)\nabla k\right] + P_k - \beta_0^*\rho\omega k$$

$$\rho\frac{\partial \omega}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\omega = \nabla\cdot\left[(\mu+\mu_T\sigma_\omega)\nabla\omega\right] + \alpha\frac{\omega}{k}P_k - \rho\beta_0\omega^2, \quad \omega = \mathrm{om}$$

$$\mu_T = \rho\frac{k}{\omega}$$

$$P_k = \mu_T\left[\nabla\mathbf{u}:\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right]$$

Model solves for momentum, energy and mass conservation

Gas viscosity is calculated from Sutherland equation

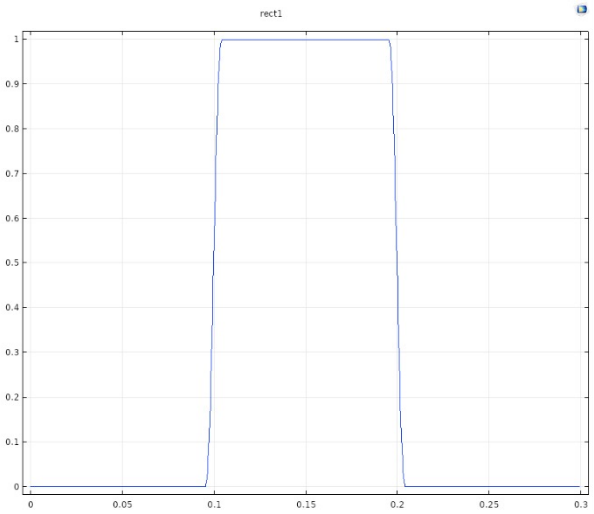
$$\mu = \mu_0\left(\frac{T}{T_0}\right)^{1.5}\left(\frac{T_0 + (110.4\ Kelvin)}{T + (110.4\ Kelvin)}\right)$$

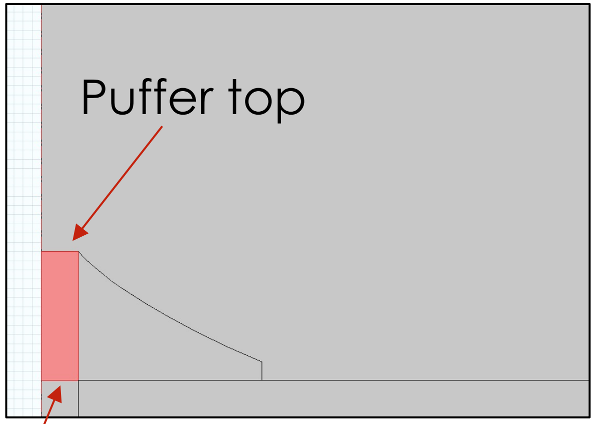
$$\mu_0 = 1.716 * 10^{-5}\frac{kg}{m * s}$$

$$T_0 = 273.15\ K$$

$$\frac{\partial c}{\partial t} + \nabla\cdot(c\mathbf{u}) = \nabla\cdot(D\nabla c) + R$$

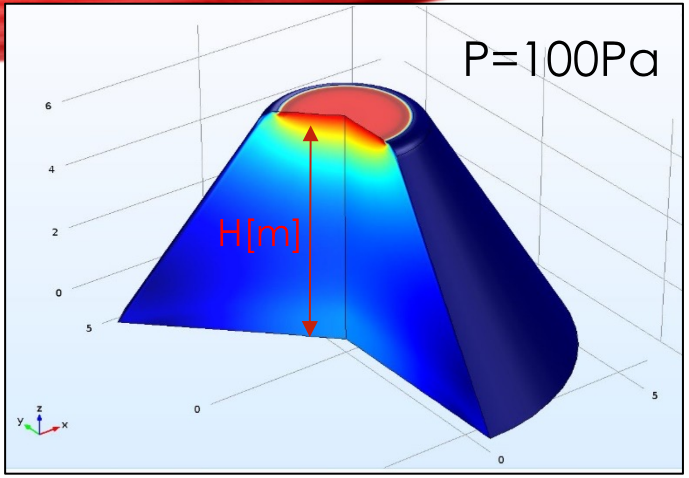
Convection and diffusion

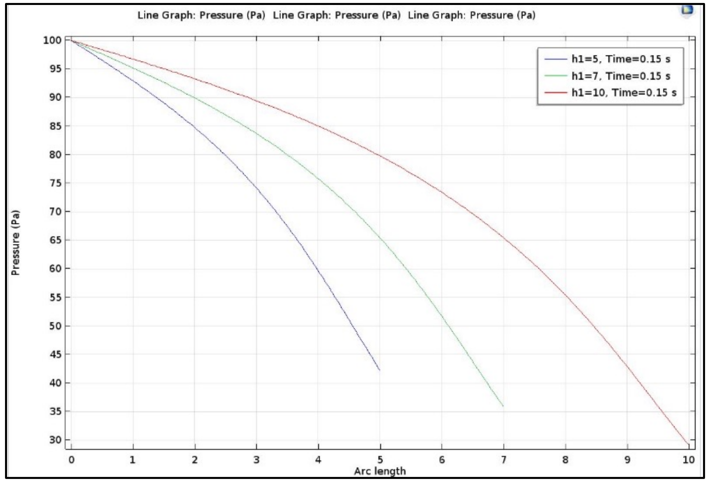


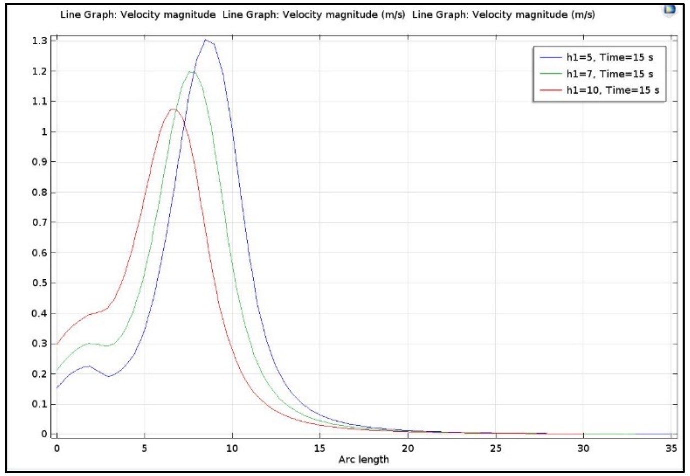


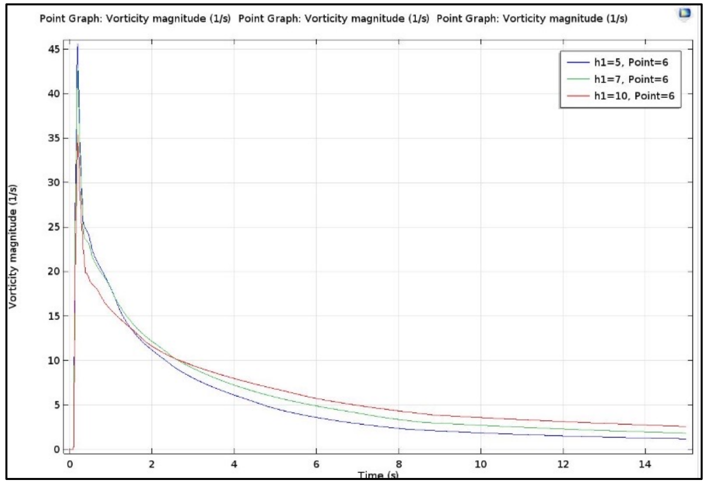
Rectangular pulse function

Geometrical Effects



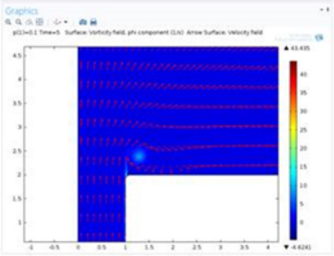




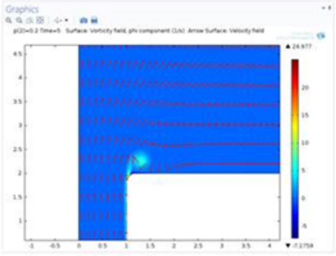


For smooth border (f>30% for flat surfaces)and f>70% for cone)no rolls-up occurs and the ring can't form anymore.

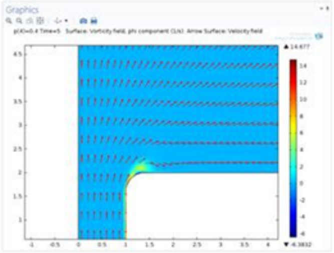
Fillet effect



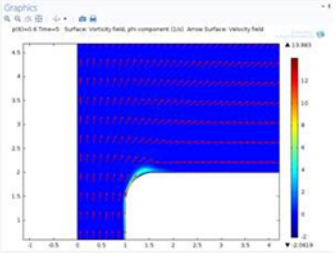
Fillet curvature radius 0.1



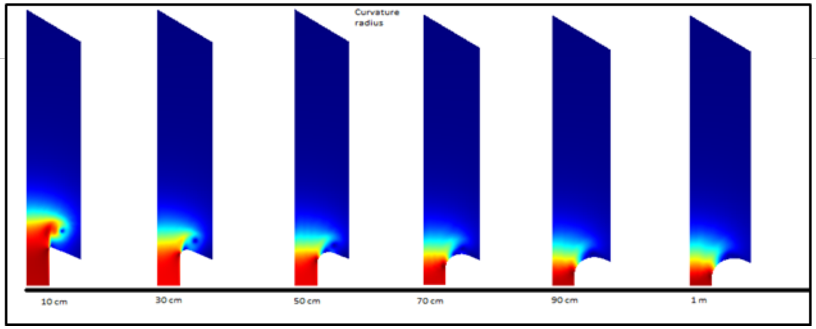
Fillet curvature radius 0.2



Fillet curvature radius 0.3



Fillet curvature radius 0.4



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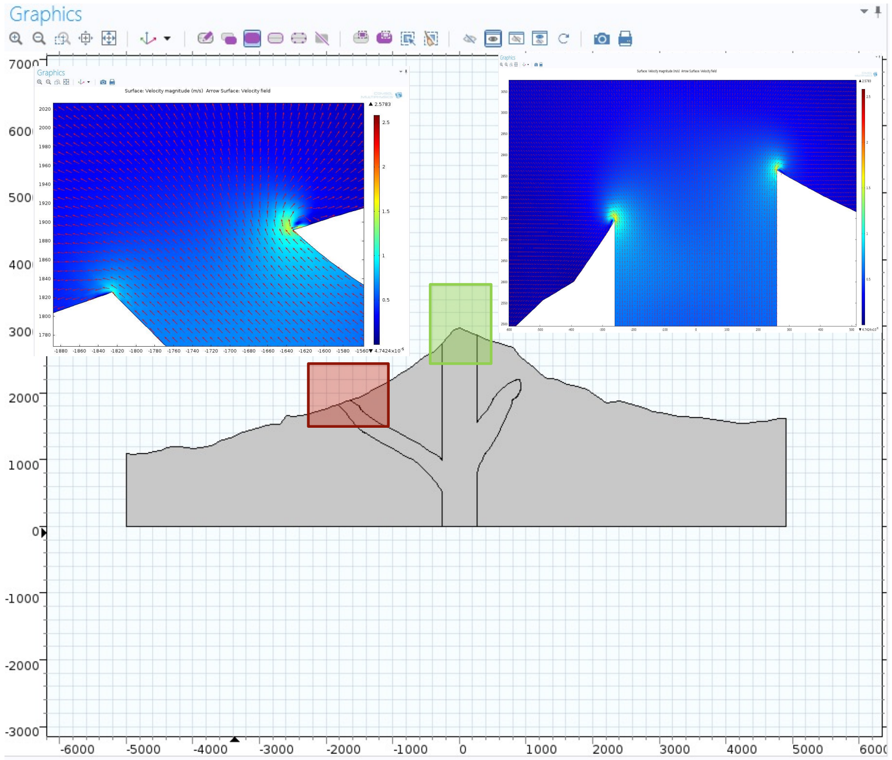
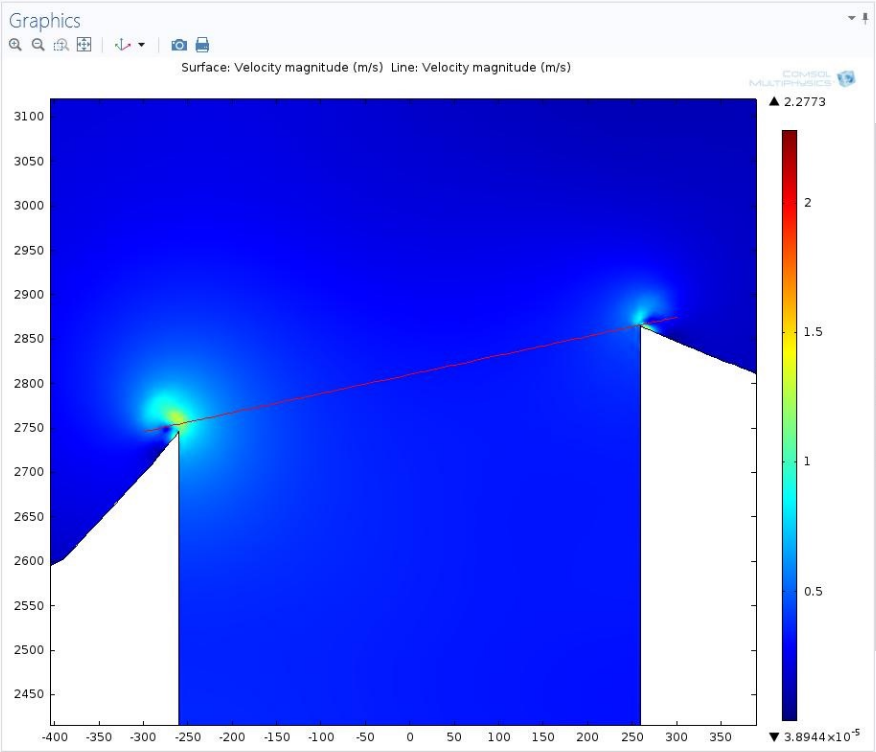
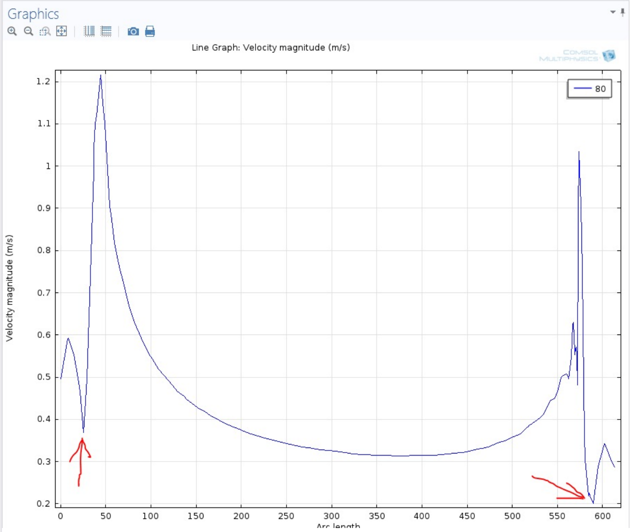
Geometrical Effects

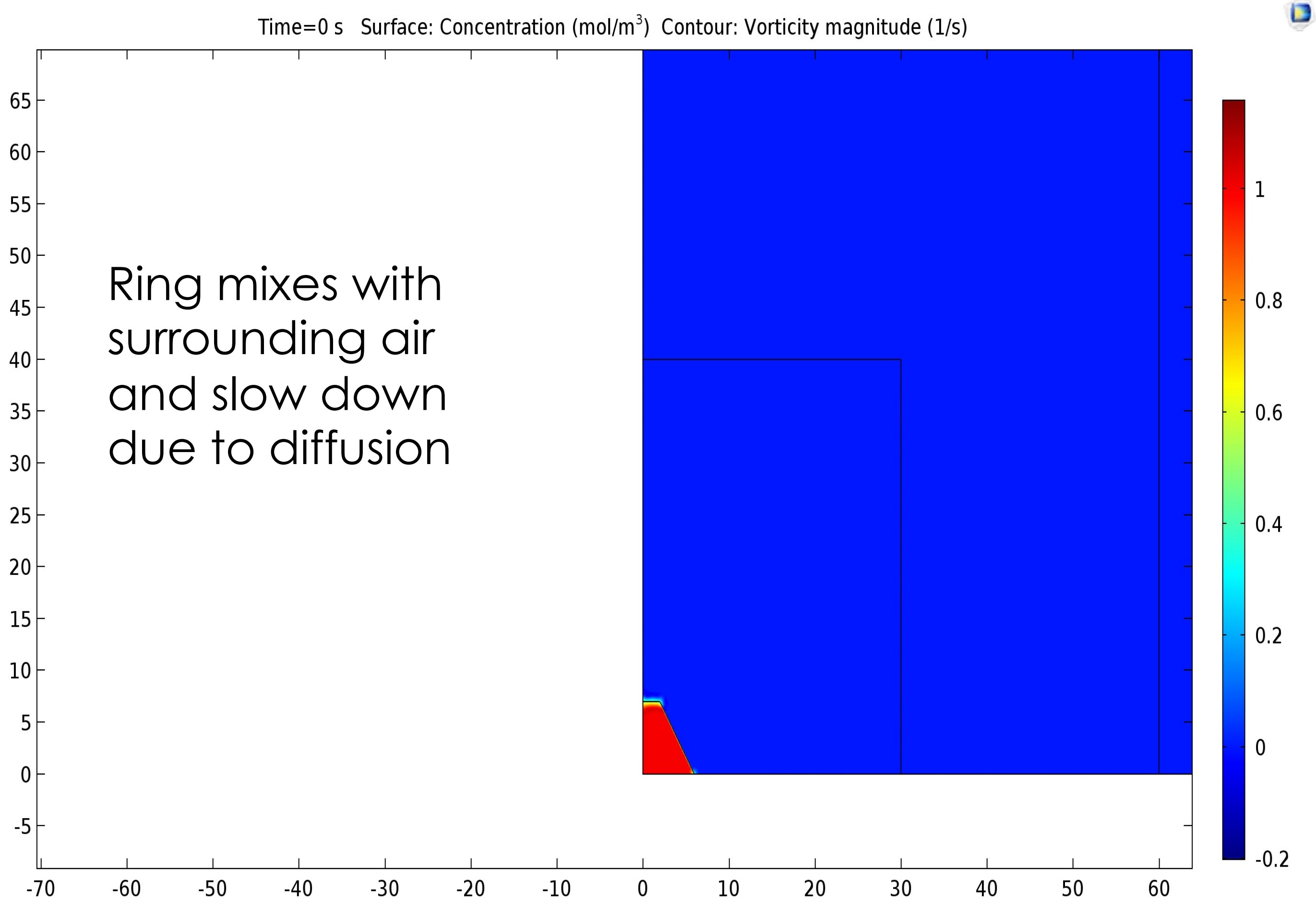




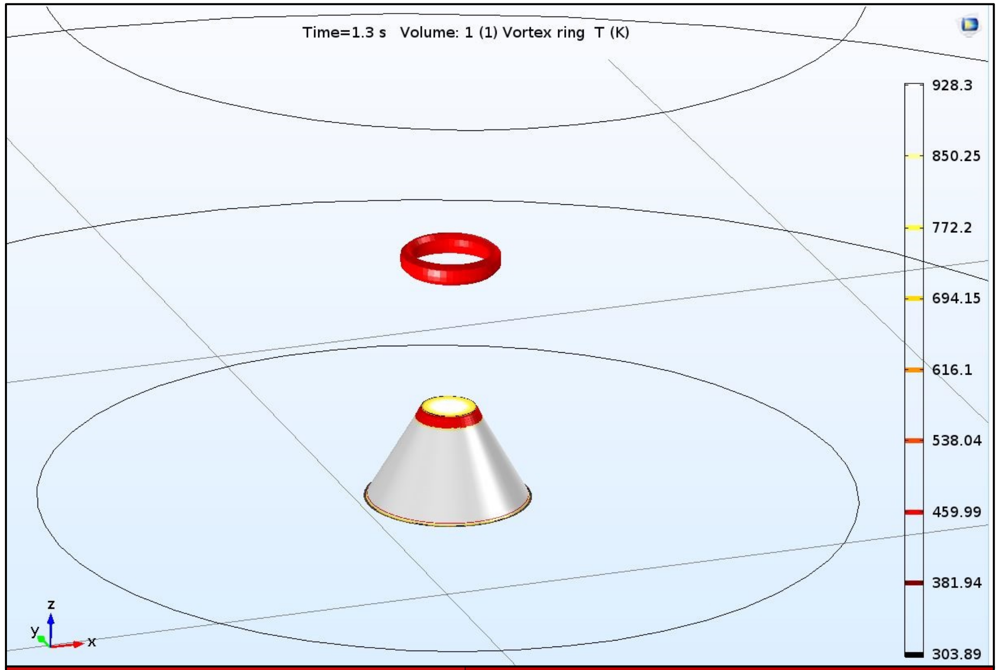


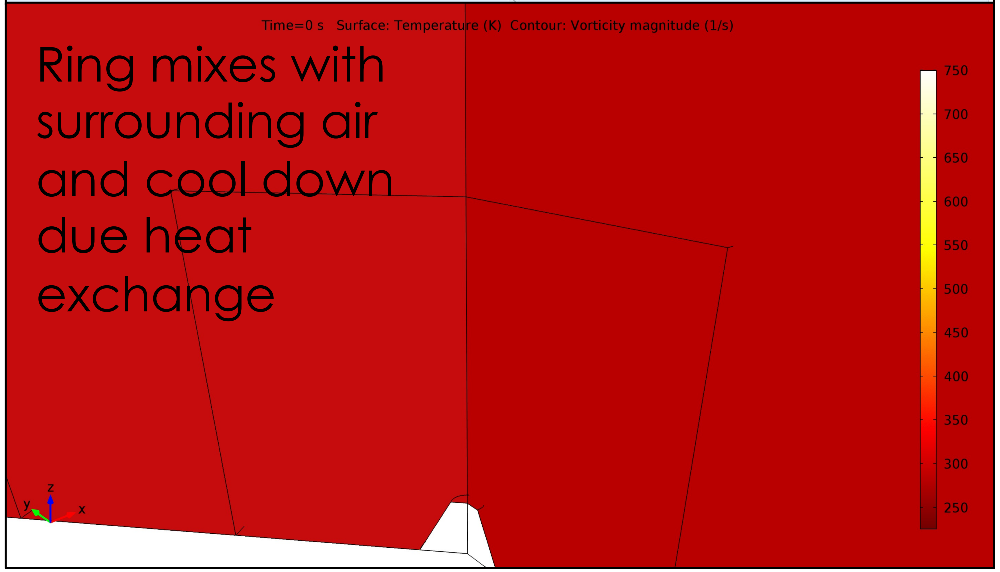
a) Ring formation is strongly influenced by the angle between conduit and the surface at vent
b) If the vent borders are at different level the ring may still form but will likely present warping

Mass transfer and thermal Effects



Ring mixes with surrounding air and slow down due to diffusion





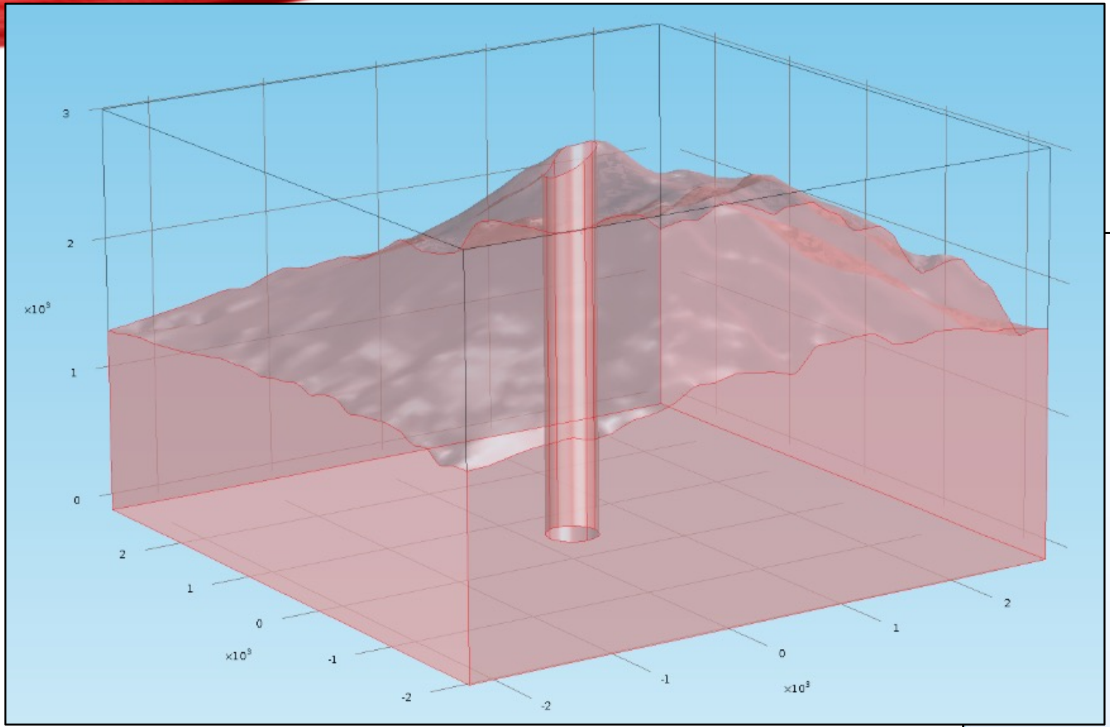
Ring mixes with surrounding air and cool down due heat exchange

Results and conclusions

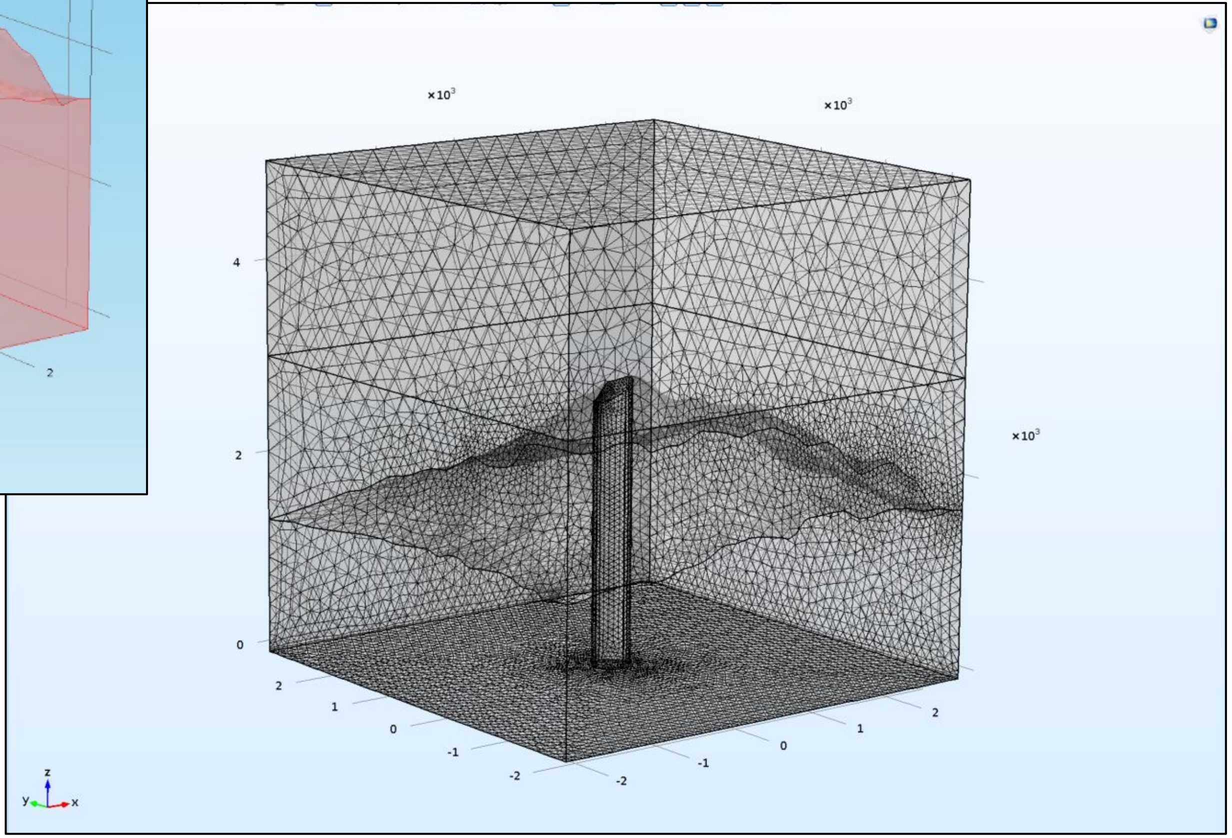
- Geometrical aspect are important to the ring generation. In particular a change in conduit height reduces exit velocities and pressure drop while has no effect on vorticity;
- Ring formation requires a well defined border with minor asymmetries (curvature radius smoothing <70%)
- Hot steam ring is subject to a rapid cooling when in contact with cold air (phase change would favour this trend)
- Mass transferred is well captured and show ring slowing by viscous diffusion.
- The effect of the overpressure is to rise up the velocity (as expected).

Conclusion: preliminary model provides more precise hints for the conditions of the hydrothermal system.

Future steps



Full 3D model with real-topography is in preparation



Turbulence will be investigated through a LES approach