

# Impact of Electro-Convection (EC) on Heat Transfer in Liquid-Filled Containers

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**Abstract:** Electric field can bring liquid in motion and thus influence heat transfer. Electro-convection (EC) can be caused by electric forces acting on a polar or nonpolar liquid, even in absence of space charge.

In this work, we studied heat transfer in a metal vessel filled by oil, with a submersed high voltage electrode serving as source of heat. Physics involved are Electrostatics and Laminar Flow with Heat Transfer.

First, heat transfer was analyzed without electric field. Then electric potential was applied to the central electrode. At low voltage, solutions are identical. Model experiments in absence of field show fair agreement with calculated temperatures.

High electric field generates intense flow and makes temperature distribution inside oil more uniform, but adds losses, which may result in a larger overheat. With a large body under voltage, the temperature rise is higher with EC than without, but with a smaller body it is lower.

**Keywords:** Electro-convection, electrostatics, heat transfer, transformer oil.

## 1 Introduction

It is known that electric field can bring liquid in motion and thus influence heat transfer. One of the early patents [1] depicts using this effect for power transformer cooling. There are two basic mechanisms:

- Related to formation of charged species (similar to electric wind in corona discharges);
- Electric forces acting on a polar or nonpolar liquid; relative permittivity must be greater than unity for this effect to take place.

We note upfront that the directions of the flows caused by these two mechanisms are the opposite. We will assume absence of ionization. Thus, the term EC is applied here only to the second mechanism.

Volumetric electric force acting on an incompressible linear dielectric whose

permittivity  $\varepsilon$  does not change through the volume is given by a formula ([1], in CGS units)

$$(1) \quad f = \frac{(\varepsilon_r - 1)\varepsilon_0}{8\pi} \nabla E^2,$$

or, in SI units,

$$(2) \quad f = \frac{(\varepsilon_r - 1)\varepsilon_0}{2} \nabla E^2 \text{ [N/m}^3\text{]}.$$

Note that (1), (2) are not a very obvious derivation from a general case that is given elsewhere (see, e.g., [1] p. 151, [3], [4]).

The physical meaning of (1), (2) is that the dielectric is pulled, irrespective of polarity, towards strong field. If this dielectric is gas or liquid, it starts moving and influences heat transfer. The physics involved are electrostatics and fluid dynamics.

On the first sight, EC is always favorable for better cooling. However, to move a mass, energy supplied by an external source needs to be invested. This energy transits eventually to heat, at least, in a closed vessel.

## 2 Estimate of Electric Force, EC Power, and Reynolds Number

We will use simple 1D geometry having an analytical solution for the electric field. Consider coaxial cylinders with inner radius  $rin$ , and outer radius  $Rout$ . Voltage  $V$  is applied to the inner cylinder. The electric field is given by a formula

$$(3) \quad E(r) = \frac{V}{r \ln\left(\frac{Rout}{rin}\right)},$$

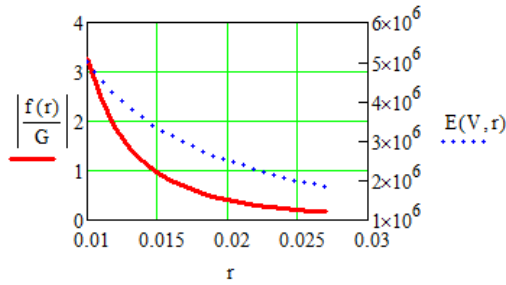
and the volumetric electric force calculated from (2) will be

$$(4) \quad f(r) = 0.5(\varepsilon_r - 1)\varepsilon_0 \text{grad}E^2(r),$$

where

$$\text{grad}E^2(r) = \frac{2V^2}{r^3 \ln^2\left(\frac{Rout}{rin}\right)}.$$

For  $r_{in}=1\text{cm}$ ,  $R_{out}=2.71828\text{cm}$ ,  $\epsilon_r = 2.3$ , and  $V=50\text{kV}$ , ratio of electric force to specific gravity, and field are shown in Figure 1. It is seen that even at a modest electric stress the electric force dominates over gravity in a large volume. (In a gas containing dipole molecules, as in a flame zone of a burner, the electric forces are orders of magnitude higher than buoyancy forces [5].)



**Figure 1.** Ratio of electric force to specific gravity ( $G=8.83 \cdot 10^3 \text{ N/m}^3$ ) in oil between coaxial cylinders (red) and field  $E$  [V/m] (blue) for  $r_{in}=1\text{cm}$ ,  $R_{out}=2.71828\text{cm}$ ,  $\epsilon_r = 2.3$ , and  $V=50\text{kV}$ .

Specific power invested by the field to bring the liquid in motion can be estimated by a formula

$$(5) \quad w = fu[\text{W/m}^3],$$

where  $u$  is liquid velocity,  $f$  is volumetric force. Assume that  $f=10,000\text{N/m}^3$  and  $v=0.1\text{m/s}$ , density  $\rho=1,000\text{kg/m}^3$ . To drive  $1\text{kg}$  at  $0.1\text{m/s}$ , we need  $P=10^4\text{N/m}^3 \cdot 0.1\text{m/s} \cdot 0.001\text{m}^3=1\text{W}$ .

The limits of laminar flow are set by Reynolds number, which can be anywhere from 2,000 to 10,000 depending on geometry and liquid. Reynolds number is

$$Re = \frac{\rho u L}{\mu},$$

where  $L$  is a characteristic linear dimension, and  $\mu$  is the dynamic viscosity of the fluid.

Adopting  $L=0.1\text{m}$ ,  $u=0.1\text{m/s}$ ,  $\mu=2 \cdot 10^{-3}\text{Pa}\cdot\text{s}$ ,  $\rho=1000\text{kg/m}^3$  we calculate  $Re=5000$ , which means that at elevated temperature laminar flow can transit to a turbulent one due to much lower viscosity.

The figures above are mainly for sanity check.

### 3 Use of COMSOL Multiphysics

We calculate heat transfer in a rectangular metal vessel  $13.5'' \times 15'' \times 6.25''$  filled by transformer oil. Heat  $Q_0$  is generated by an internal body (an ellipsoid of revolution with semi-axes of  $100\text{mm}$  and  $50\text{mm}$ ; larger axis is horizontal) sitting at a high potential  $V_0$  relative to the grounded vessel. See Figure 2 for details.

The electrostatic problem (Laplace equation) is solved using the Electrostatic interface. Electric field components determine the volume forces (2), in addition to gravitational forces. Then Laminar Flow with Heat Transfer interface is used. Thus, the problem is studied for low Reynolds numbers. Laminar flow is described by the equation

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left[ -p\mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) \right] + \mathbf{F}$$

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot (\mathbf{u}) = 0$$

where

- $\mathbf{u}$  is the velocity vector;
- $p$  is the pressure (SI unit: Pa);
- $\mathbf{F}$  is the body force vector (SI unit: N/m<sup>3</sup>).

Heat transfer is defined by the equation

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q + Q_{vd} + Q_p,$$

where

- $C_p$  is the specific heat capacity at constant pressure;
- $T$  is the absolute temperature;
- $k$  is thermal conductivity
- $Q$ 's are heat sources.

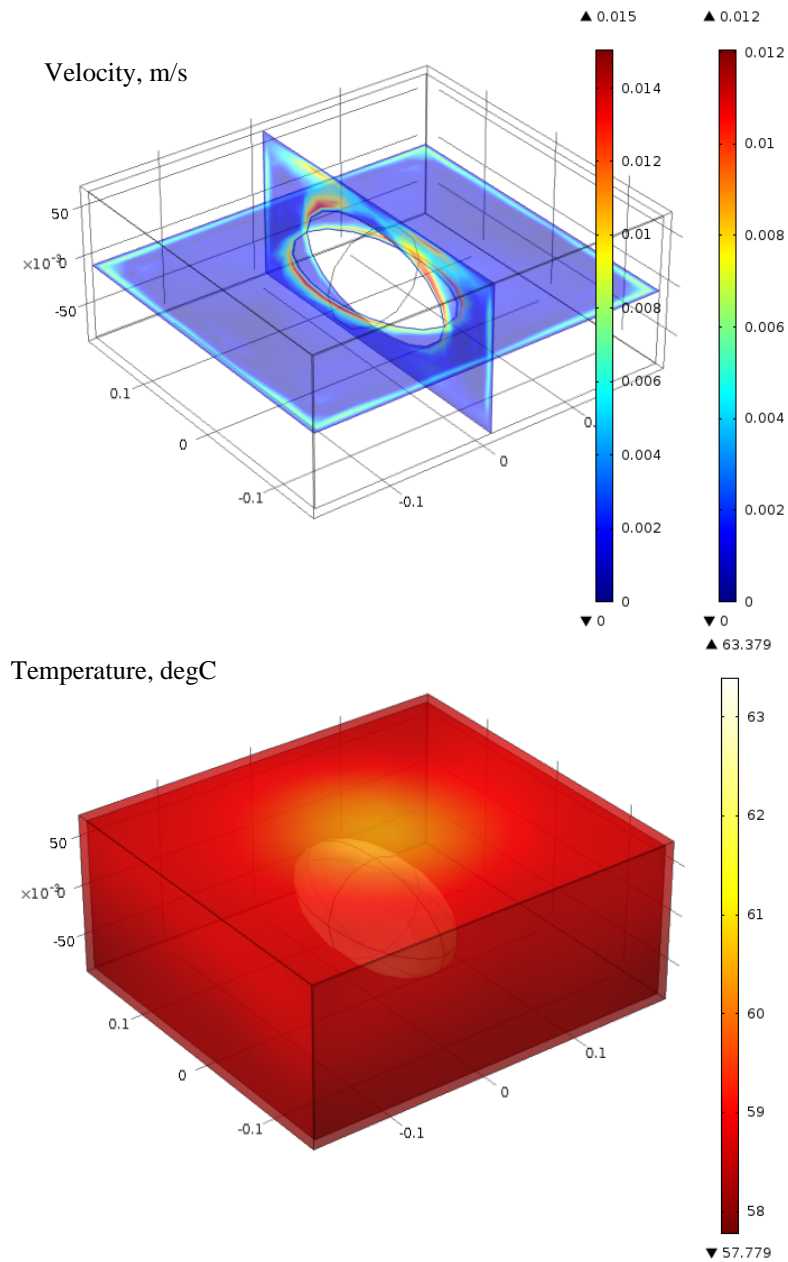
Internal boundaries are defined as non-slip. The external cooling conditions are natural convection in air and radiation with surface emissivity of 0.95; vessel bottom is heat-insulated. Materials used are aluminum and transformer oil. Properties of the latter are defined in Comsol Material Library.

## 4 Results

### 4.1 Simulations

Total power dissipated in the inner aluminum electrode was 150W. Heat transfer was analyzed first without electric field. Then “infinitesimally” small voltage ( $V_0=1V$ ) was applied. Both transient and steady-state solutions have been

obtained for the above cases. All results were virtually identical (for transient solution, temperature had stabilized after  $t > 50,000s$ , and the velocity profiles were established much faster). Then high voltage (HV) was applied. Figure 2, Figure 3 show velocity profiles and temperature distribution for the cases without and with electric field, respectively.



**Figure 2.**  $V_0=0$ ,  $Q_0=150W$ . Ambient  $T_0=23degC$ . Transient solution, Time=50,000s.

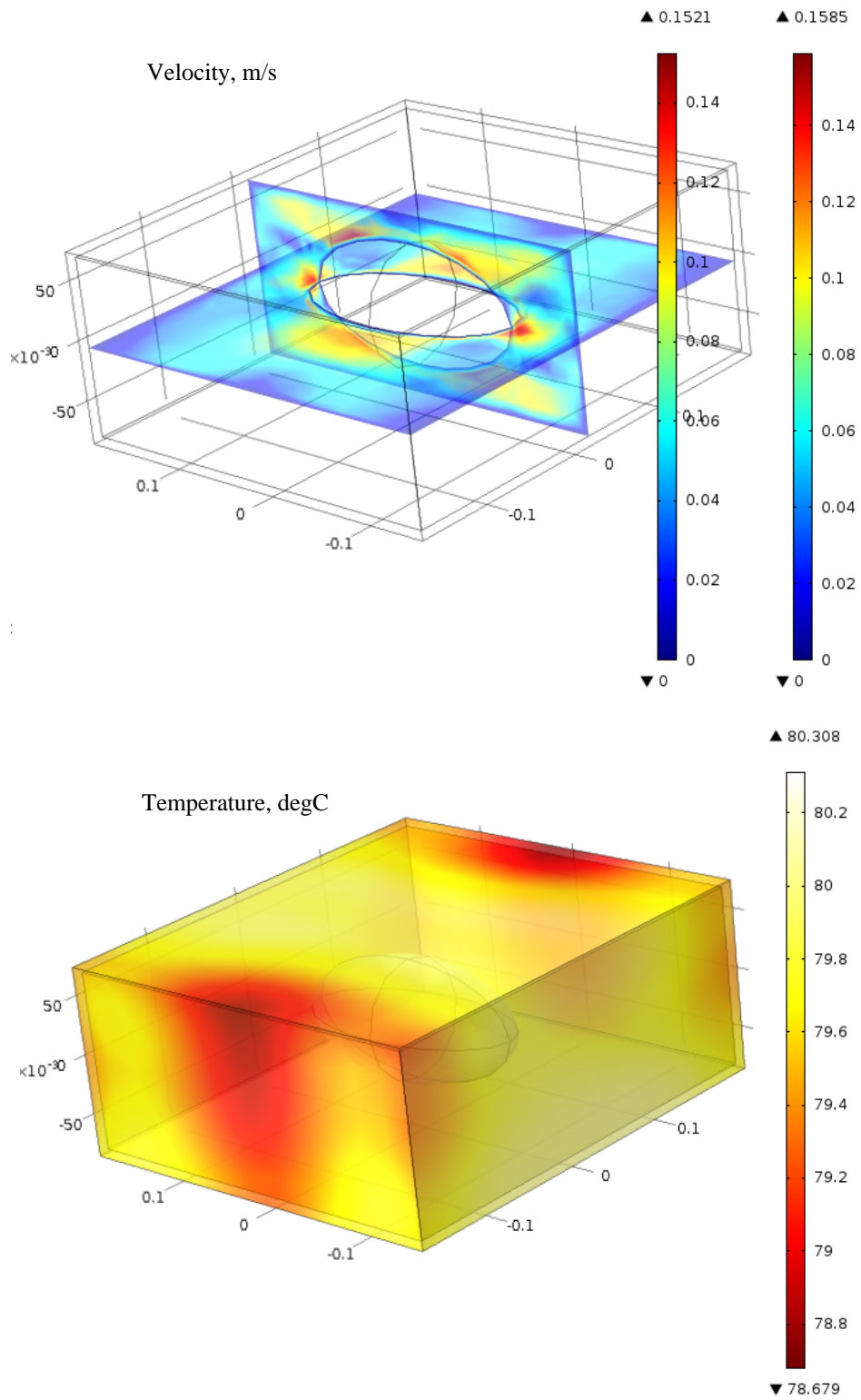


Figure 3.  $V_0=80\text{kV}$ ,  $Q_0=150\text{W}$ . Ambient  $T_0=23\text{degC}$ . Transient solution, Time=50,000s.

It is seen that in presence of HV, electric field generates intense flow, and that stronger flow is in the region of higher electric field, i.e., where the HV electrode has larger curvature, Figure 3, as opposed to natural convection Figure 2.

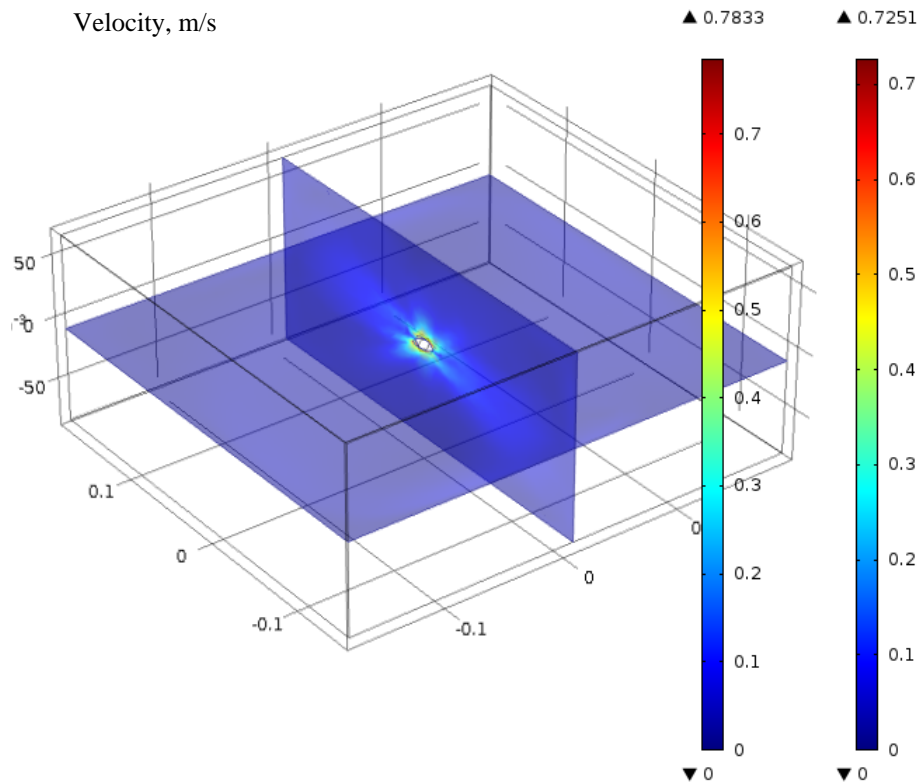
Strikingly, the overall overheat is larger in the presence of electric field. The physical meaning is that additional losses are generated by viscous heating; the energy for that must be supplied by the voltage source. (It is unclear to us how Comsol software actually accounts for that.) Thus, EC may move heat away from heat sources, equalizing temperature distribution, at the penalty of increasing *maximum* temperature,  $T_{max}$ . Two additional simulations have been performed to investigate this effect further.

First, the ellipsoid size was reduced dramatically (semi-axes were 10mm for the horizontal one, and 5mm). Without electric field,  $T_{max}$  was 160degC at the ellipsoid. With field, at

80kV, maximum oil velocity reached 0.8m/s Figure 4, but overheat was virtually the same as without electric field with the large ellipsoid Figure 2. In another scenario, the ellipsoid was “mid-size” (semi-axes 50mm, 25mm), and, optionally, the flow was arrested by a cylindrical solid dielectric shell Figure 5.

The shell material was ascribed the same permittivity as oil, and thus the shell had no impact on electric field distribution in *electrostatic* formulation.

Maximum temperature was lower than with the large ellipsoid, both with and without the shell Figure 5. We infer from these simulations that smaller amount of liquid residing in the region of strong field needs less energy to bring it into motion.



**Figure 4.** Very small ellipsoid, semiaxes a=5mm, b=10mm, c=5mm.  $V_0=80\text{kV}$ ,  $Q_0=150\text{W}$ .

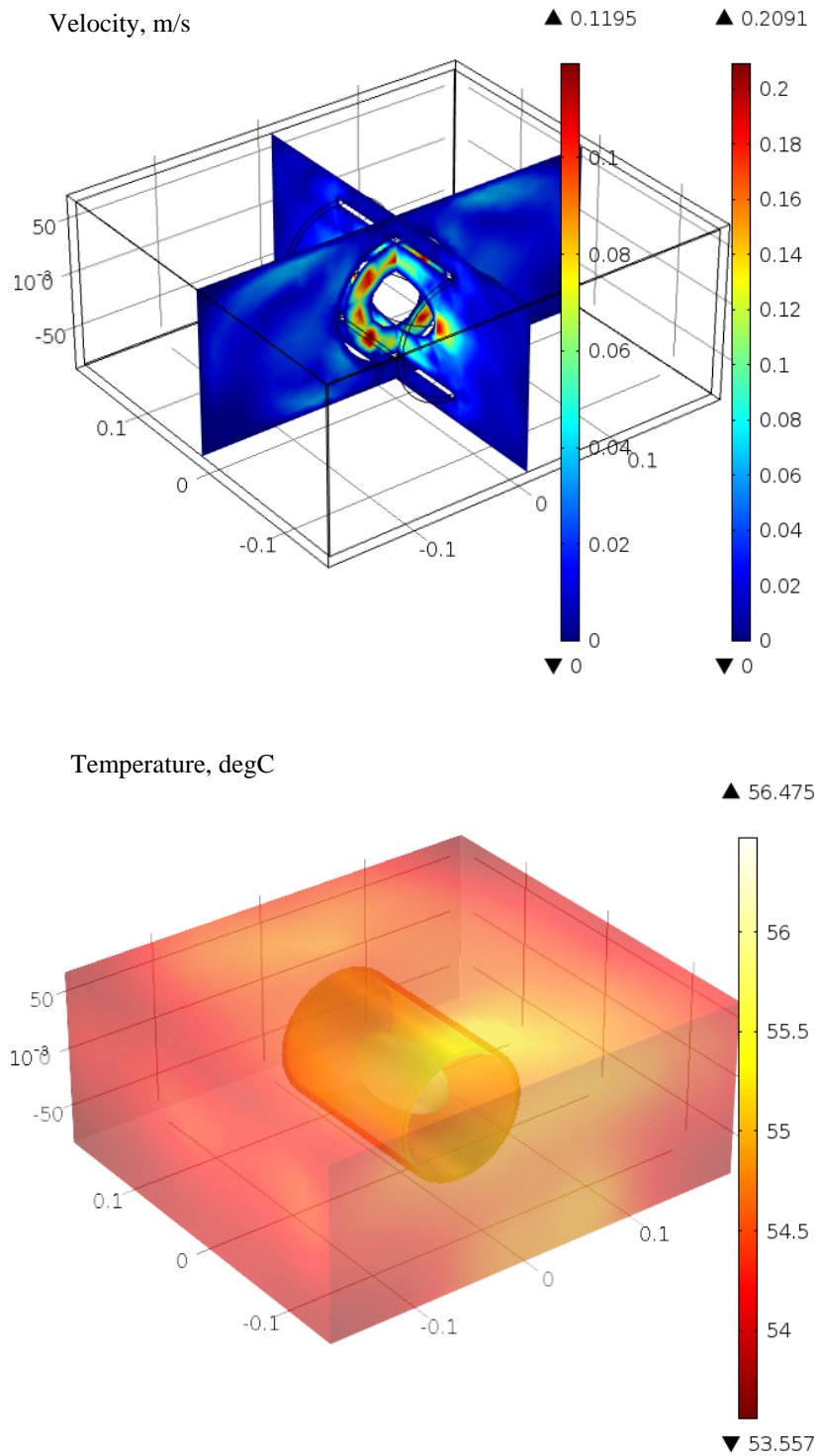


Figure 5. Stationary solution.  $V_0=80\text{kV}$ ,  $Q_0=150\text{W}$ . Dielectric cylinder  $\epsilon_r=2.3$ .

We note that in a more rigorous approach, the electric field distribution at *direct current* should be computed using materials' conductivities rather than permittivities (see details, e.g., in [6] and its bibliography, and [7]). The electric problem becomes highly-nonlinear because conductivities change by orders of magnitude in a relatively narrow temperature and electric field range. Such treatment is beyond the scope of this work.

## 4.2 Experimental

A rectangular metal container with dimensions as indicated in the Simulations Section, painted black, was filled with transformer oil. Heat was provided by a stack of large low-value resistors placed inside and energized by electric current at *low* voltage. Thus, the experiment was conducted in absence of electric field. Temperature was measured in multiple points both inside and outside the container by thermocouples. With the container placed by wide side on a heat insulating surface, at ambient temperature 23degC, the experiments showed fair agreement with calculated temperatures Figure 2.

## 5 Conclusions

EC in absence of ionization was simulated in a model geometry using multiphysics tools. The described method can be useful for understanding and simulating electrohydraulic phenomena in liquids and gases. Turbulent flow and the mechanism of electrical energy conversion to heat as indicated by this study can be a subject of further modeling with Comsol. Experimental work can include measuring temperature and velocity profiles, as well as power consumed from HV source, in presence of electric field.

## 6 References

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