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Mystery Well: Chemical-engineering solution to the internal rain problem

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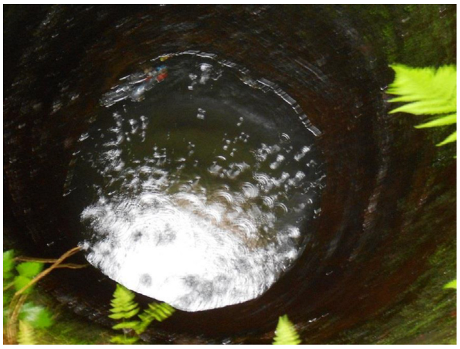
HIGHLIGHTS

- Rainy well as a multiphase reactor.
- Onset of humidity-driven convection.
- Buoyancy driven circulations.

GRAPHICAL ABSTRACT

Mystery Well with internal rain.



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ABSTRACT

There are occasional evidences about a strange phenomenon of permanent internal rain in water wells (a mystery). This challenge was recently accepted by a group of enthusiasts who measured the basic data inside such a'Mystery Well' (temperature, humidity, aerosol particles, rain drops, etc.). As aerosol chemists, they suggested a possible explanation in terms of a nucleation reaction kinetics in a cloud chamber. They concluded that it was not the whole story and the internal flow dynamics should also be taken into account, namely the occurrence of large-scale circulations.

The motivation of this study is to contribute to the problem from the chemical-engineering point of view, considering the Mystery Well to be a multiphase contacting/reacting/transporting system. The goal is to show that the anticipated convective circulatory motions can really develop. A simple model is suggested, based on the available data and elementary theoretical reasoning (evaporative convection, thermal instability, Rayleigh number, buoyant flows, dew point, multiphase effects). The instability condition for the Rayleigh-Benard convection is formulated. The estimated actual Rayleigh number Ra is by a few orders higher than the critical value ($Ra^* \sim 10^5$), indicating the presence of convective motions. A simple mechanism for the rain formation is suggested, different for both year seasons. In summer, the evaporation driven convection ($Ra \sim 10^9$) could develop in the lower isothermal and cold part of the well (8 °C), where the vapour saturated light air ascends and penetrates into the thermally stably stratified upper zone. This up-flow is compensated by the down-flow of the warm humid air from the ambient (24 °C) that reaches the dew point and the vapour precipitates. In winter, the whole gas layer in the well is doubly unstably stratified, by both the thermal (bottom 8 °C, ambient near 0 °C) and humidity (bottom 100%, ambient about 80%) vertical profiles. The estimated Ra-values for the thermal ($Ra \sim 10^{13}$) and the humidity ($Ra \sim 10^{11}$) convections are above the critical. The model prediction is compared with the published experimental data obtained in the summer season.

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Nomenclature

Symbols

a,b,c	model parameters
A	aspect ratio [–]
D	well diameter [m]
g	gravity [m/s^2]
h	relative humidity [–]
H	well height, convective layer height [m]
K	wall-effect coupling factor [–]
M	molar mass [kg/mole]
p	pressure [Pa]
R	universal gas constant [J/mol·K]
Ra	Rayleigh number [–]
t	Celsius temperature [°C]
T	thermodynamic temperature [Kelvin, K]
z	vertical coordinate [m]

Greek symbols

α	thermal expansivity [1/K]
δ	molecular diffusivity [m^2/s]
κ	thermal diffusivity [m^2/s]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
Δ	difference

Indexes

a	dry air
c	critical value of Ra, infinite layer
d	dew point
LZ	lower zone
m	mean
w	water vapour
s	saturation value
t	total value
UZ	upper zone
0	reference state
1,2	bottom and top locations
*	critical value of Ra, finite layer

Abbreviations

BC	boundary condition(s)
ITC	isothermal case
LZ	lower zone
NTC	non-isothermal case
UZ	upper zone

1. Introduction

In a recent article (Hovorka et al. 2015, denoted as H15), the authors introduce the problem of a water well with spontaneous internal rain (Mystery Well). The well is of a cylindrical shape (2.4 m dia and 19 m deep) dug in the argillite rock with bricks for the upper wall (about 7 m down from the top entry). There must be a physical mechanism perpetually generating layers of fine water drops from within the interior space of the well that keep falling on the water surface underneath. The mechanism should be robust since the rain can be observed over the year's seasons. It was suggested that fine aerosol particles from the ambient air continuously flow inside the well, meet the slightly over-saturated wet air, serve as the cloud condensation nuclei, and grow into drops that eventually descend. It was also suggested that there might be some convective motions, which could enhance the particles inflow, since their sedimentation and diffusion transport is relatively slow. The particle size was assessed to likely be that of the accumulation mode (ca. 0.1–1 μm).

The goal of this study is to investigate the possibility of the development of the natural circulations inside the well, based on the Rayleigh-Benard instability of buoyant layers. In Section 2, an idealized convection model is introduced, where the adverse density gradient occurs due to the vertical profile of air humidity. In Section 3, the model is made more realistic by considering the experimental data from H15.

2. Idealized model of the well

Consider a cylindrical container of diameter D and height H, filled with air, see Fig. 1. A reservoir of water is at the bottom (z = 0) and that of air is at the top (z = H). The reservoirs are large enough to secure the constancy of the temperature (T_1, T_2) and the air relative humidity (h_1, h_2) at the bottom and top boundaries (# 1, 2). Consider first the isobaric and isothermal case. Everywhere the air layer has constant total pressure p_t and temperature T_0. The bottom humidity h_1 is the equilibrium saturation value, and at the top $h_2 < h_1$ is some other ambient value. The density of air-water vapour mixture decreases with humidity,

$$\rho = (p_a.M_a + p_w.M_w)/RT, \quad p_a + p_w = p_t \tag{2.1}$$

because the water molecules (M_w = 0.018) are lighter than the air molecules (M_a = 0.029), with the difference ΔM = 0.011 kg/mole. Here, p_a and p_w are the partial pressures of air and vapour in the mixture of total pressure p_t, T is temperature in Kelvins and R is the universal gas constant. Dry air pressure p_a obeys the ideal gas equation. The actual vapour pressure p_w relates to the saturation vapour pressure p_s via humidity:

$$p_w = h \cdot p_s \tag{2.2}$$

Saturation pressure p_s is an increasing function of the temperature,

$$p_s = 611 \times 10^{(7.5t/(t+237.3))}, \quad t = \text{Celsius degrees}(^\circ\text{C}), \quad t = T - 273, \tag{2.3}$$

So the dry-wet air density difference increases progressively with rising temperature. The mixture density formula then is

$$\rho = (p_t.M_a - \Delta M.p_s.h)/RT. \tag{2.4}$$

The air-water data can be found in numerous sources (e.g. ASHRAE Handbook Fundamentals, 2017, Olivieri 1996; Rabinovich and Beketov 1995; Wagner and Kruse 1998; Wexler 1965).

The density difference across the layer $\Delta\rho$ = (ρ_2 - ρ_1) corresponds to the humidity difference Δh = (h_1 - h_2). Since the bottom humidity h_1 is larger, the bottom density ρ_1 is lower. Such a top-heavy/bottom-light configuration is potentially unstable, depending on the steepness of the vertical density gradient. It follows from the linear stability analysis of laterally unconfined thermal layers (Chandrasekhar 1961; Drazin and Reid 1981), that the appropriate dimensionless measure of this gradient is the Rayleigh number,

$$Ra = g.\Delta\rho.H^3/\rho.\nu.\delta, \tag{2.5}$$