Analysis of Mash Tun Flow: Recommendations for Home Brewers

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Abstract: The paper describes work designed to help home brewers better understand the fundamental aspects of fluid dynamics inside mash tun reactors. Beer can be manufactured at home rather simply using a picnic cooler as mash tun reactor but the production of a good quality brew requires continuous experimentation and understanding of the fundamental processes inside the reactor. This paper describes work devised to investigate the variations in performance of home-made mash tun reactor designs associated with the physics of the flow of water through the porous bed of malted grains. Using the model, various proposed mash tun reactor configurations were examined and evaluated and a set of recommendations for home brewers was developed.

Keywords: Mash tun reactors, brewing, porous media flow, reactor design

1. Introduction

The major steps in the beer making process are rather simple a quite good brew can be produced using a common picnic cooler. First, grain (usually barley) is wetted and allowed to partially germinate before dried in a kiln (malting) in order to convert starch reserves within the grain into more easily fermentable sugars. Next, the malted grains are soaked in hot water to extract the fermentable sugars and then rinsed slowly to ensure as much sugar is removed as possible. This step is the called "mashing," and the device in which it is conducted is called a "mash tun." The mashing process is critical to the final taste, aroma, color, and body of the beer, and provides an excellent opportunity to use science and technology to improve the home brewing experience.

Mashing can be further broken down into the initial steeping step (where the grains simply sit in hot water) and the subsequent rinsing step (called sparging). After the malted grains are crushed in a mill in order to facilitate complete hydration and expose the inner grain material, they are combined with hot water (usually at a temperature of 160 to 165°F) in the mash tun and allowed to sit there for some period of time, usually around 1 hour. The mash temperature should settle at a temperature between 150 and 155°F, and kept there for the entire steeping time. Any off-the-shelf plastic cooler will provide the thermal insulation required of a beginner to intermediate homebrewed.

To calculate the extraction efficiency of a beer one must know/measure the specific gravity. This is readily done using a hydrometer. Specific gravity of beer generally varies between 1.005 and 1.150, and is usually expressed in "points," where the leading 1 is dropped and the remainder is multiplied by 1000. For example, a specific gravity reading of 1.040 would be 40 points.

The concentration of sugar in the wort is calculated in ppg (specific gravity points per pound per gallon), called c_{wort} [1]:

$$c_{wort} = \frac{V_{wort} \cdot BG}{m_{malt}}$$

In this equation, V_{wort} is the total volume of wort in gallons, BG represents the original specific gravity of the boil in points (also the specific gravity of the wort after it leaves the mash tun), and m_{malt} is the mass of the malt used in the mash tun in pounds. Once this value is determined, it can be compared to the maximum potential yield from the malt. The following equation defines the extraction efficiency of a beer:

$$e_{extract} = \frac{c_{wort}}{c_{\max}}$$

(where $e_{extract}$ is the extraction efficiency and $c_{\max}$ is the maximum yield for the given malt in ppg). Typical home brewer extraction efficiency values average around 75%.

A mash tun reactor must always include a filter of some kind to allow for hot water to run through the grain and carry the sugar out while leaving the grain husks. The differences in how this filter is designed are the primary drivers of the efficiency of a mash tun. For home brewers, a popular design for filtering is the slotted pipe manifold.

Highly efficient setups are desirable since a highly efficient mash produces a higher sugar output per grain input. While continuous sparging techniques increase extraction efficiency, they also bring with them an increased risk of over extraction and poor wort quality due to the presence of undesirable flavor compounds. Interestingly, wort quality has been found to correlate to the uniformity of flow of water through the mash tun [2]. In order to analyze the extraction efficiency and wort quality of a mash tun, computational fluid dynamics simulations were performed using the COMSOL Multiphysics software. The results of this experience are described in this paper.

2. Description of the System

The mash tun reactor of this study had the dimensions of an average rectangular cooler often used by home brewers (~ 12" x 12" x 21"). The reactor was assumed to be initially full with a mixture of malted grains and water. Along the bottom of the reactor a pipe manifold filter was used. The investigation of the effects of various pipe manifold designs on the extraction efficiency was one of the key objectives of this study.

Flow through the grain bed can be analyzed using Darcy's law for flow through porous media:

$$q = -\frac{K}{\mu} \cdot \nabla p$$

where K is the permeability of the porous medium (in units of "Darcy" or square meters), μ is the dynamic viscosity of the fluid, and ∇p is the pressure gradient vector [3].

Flow anywhere outside of the grain bed (in the pipe manifold, as well as in the water level above the grain bed) was assumed laminar flow and evaluated using the Navier-Stokes equation.

Gravity was the only body force applied. All fluid regions of the model were held at 155 degrees Fahrenheit, a common sparging temperature.

A further assumption is that the sparge velocity was 0.18 [gal/min/ft^2]. This value has been recommended for optimal starch conversion.

3. Use of COMSOL Multiphysics

COMSOL Multiphysics was used to model fluid flow through the grain bed and pipe manifold. Ideally a single, accurate 3-dimensional model including all relevant features would be used to evaluate different mash tun configurations (Figure 1), but due to computation limitations this was not feasible.

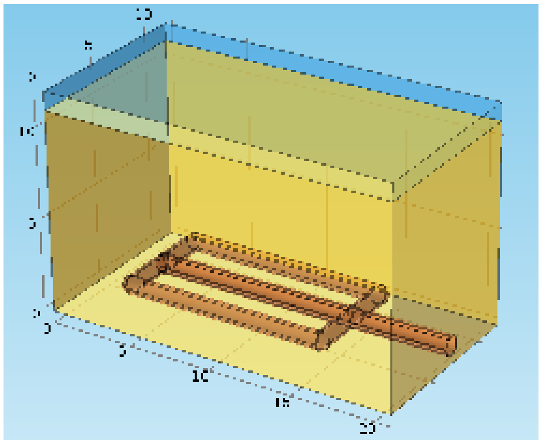

Figure 1. Schematic representation of the home brewer mash tun reactor.

In place of a single 3D model, two types of 2-dimensional models were used to model the system. These models were constructed by by taking various x-y plane or y-z plane cuts (Figure 2) and modifying individual features. These different planar cuts were evaluated separately, but they approximate the 3-dimensional parameter modification when all results are viewed in aggregate. In this way, no model considered all of the applicable factors at once, but the results can be combined from the various models to develop an ideal mash tun design.

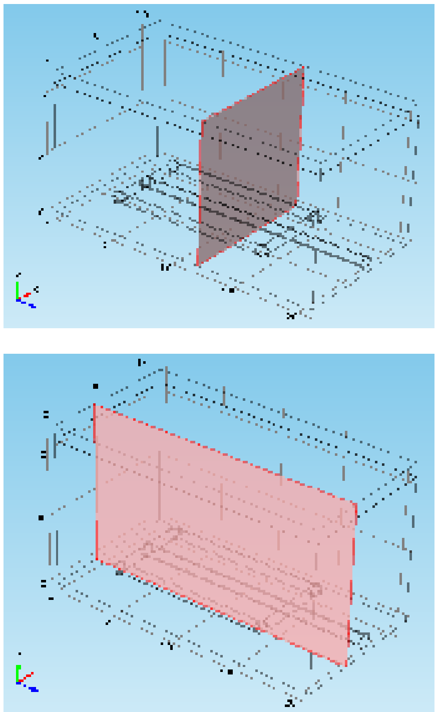

Figure 2. x-y and y-z cuts of the 3D geometry for the 2D models.

Design parameters investigated included the number of pipes in the manifold and the number of slots in each pipe (See figure 3).

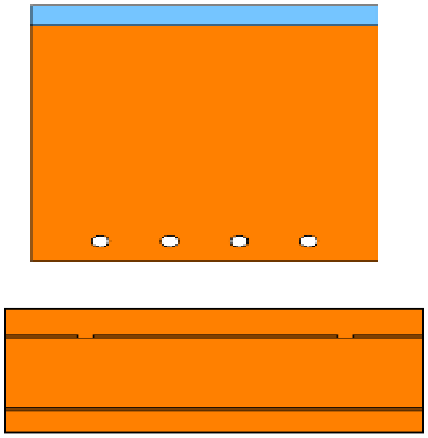

Figure 3. x-y and y-z (detail) cuts of the 3D geometry for the 2D models showing a four pipe manifold and two pipe slots .

To incorporate the potentially significant effects of sugar concentration within the wort and subsequent density and viscosity increase, two separate materials were used for the fluid regions in the COMSOL models. The small fluid region sitting on top of the grain bed was given properties of pure water, using the built-in Water option from the COMSOL material database. For the fluid through the remainder of the model, a custom material called Wort was created and given average fluid property values for wort: specifically, a viscosity of 1.5 mPa*s and density of 1050 kg/m^3 (equal to a specific gravity of approximately 1.050, which is an average pre-boil gravity).

To model the flow in the reactor the COMSOL Multiphyscis module Free and Porous Flow was used that easily allowed coupling the two flow regions. The permeability of the bed was assumed K = 9.87 e-11 m^2 [4] and the porosity was assumed uniform and equal to 0.3. To model the pipe manifold the built-in copper material properties from the COMSOL material was used. To simulate the hindering effect of the slots on the flow in the x-y models a permeability 100 times smaller than in the grain bed was assumed to apply.

For boundary conditions, at the inlet (the free upper surface of the reactor) an incoming flow of water equal to 0.18 [gal/min/ft^2] was prescribed. This converts to approximately 1.2224 e-4 [m/s]. The outlet was given a pressure condition of 0 Pa, with no viscous stress.

The method used to compute extract efficiency and wort quality was fairly simple. Concerning extraction efficiency, when using a continuous sparging technique with constant flow at the inlet and outlet, flow through the grain bed is distributed about the ideal velocity recommended by Narziss, about 1.224 e-4 [m/s]. After running a simulation, a histogram plot can created showing frequency of velocities through the grain bed. These plots were then used to evaluate extraction efficiency and wort quality. By making the assumption that the ideal Narziss velocity provides 100% extraction of sugars from the grain and into the wort. It follows that any velocity in the grain bed that exceeds this value will also provide 100% extraction while any velocity below this value would provide less than 100% extraction.

Regarding wort quality, for the purposes of this project**,** areas of the grain bed with velocities in excess of 100% are considered oversparged. These oversparged regions are where the danger of poor wort quality lies. Exposed to high flow, these areas of grain will be subject to tannin extraction. The histogram plots generated by COMSOL were used to determine the percent of the grain bed that was oversparged, and this provided another performance indicator for evaluating the various mash tun configurations.

4. Results

Figure 4 show the computed streamlines and constant pressure lines on the x-y plane for the single pipe mash tun reactor.

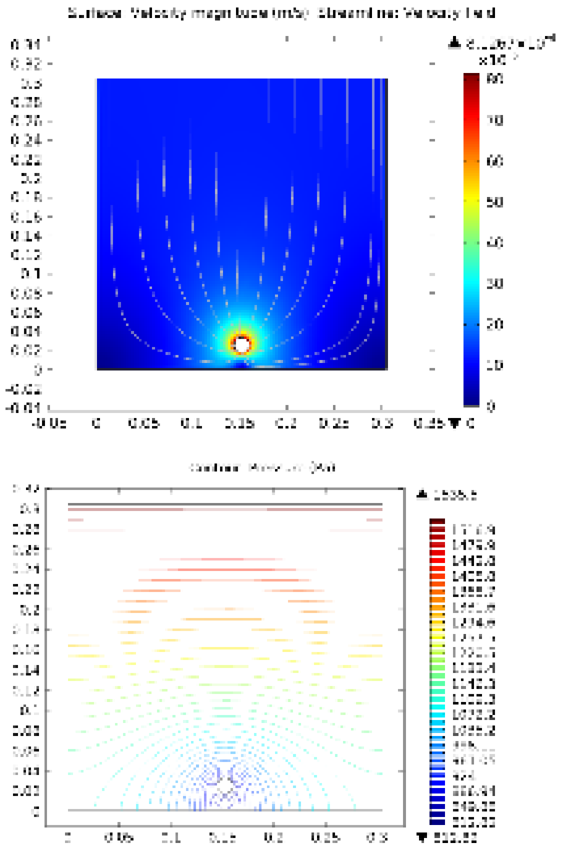

Figure 4. Computed streamlines and pressure contours for the single pipe mash tun reactor.

Using the 1D plot feature in COMSOL, results from each new model were mapped to a histogram plot that quantified the percentage of the grain bed experiencing specific velocity levels. For simplicity, the histogram was broken up into 20 sections between 0 m/s and the ideal velocity. Figure 5 shows such a histogram for the single pipe reactor.

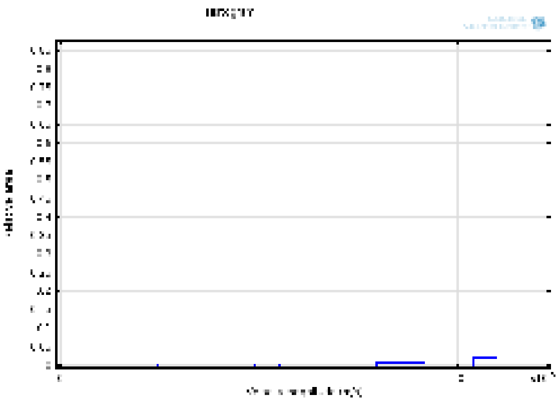

Figure 5. Histogram showing the distribution of velocities through the grain bed.

The relative area of the bed that is subject to each particular velocity was then multiplied by the extraction efficiency at that velocity and the results added together to give a representation of the total extraction efficiency. The efficiency for this example configuration was calculated to be about 95%.

The figure shows that the velocity of the flow in some areas of the bed is relatively large. These areas may be considered oversparged and be the source of poor wort quality. The percentage of the grain bed that is oversparged can be evaluated by simply plotting the percentage of the bed experiencing a velocity greater than the ideal velocity. It can be easily seen from the resulting histogram that about 42% of the bed is oversparged.

While the exact percentages found through the simulations may not directly correlate to real-world testing, predictions of significantly improved performance metrics due to certain design variations are expected to transfer well to real-world mash tun builds.

Mash tun reactor designs containing four and eight pipe manifolds were also investigated. Figure 6 is a schematic representation of a four pipe manifold reactor and figure 7 shows the computed streamlines for this configuration. This figure should be compared with figure 4 above.

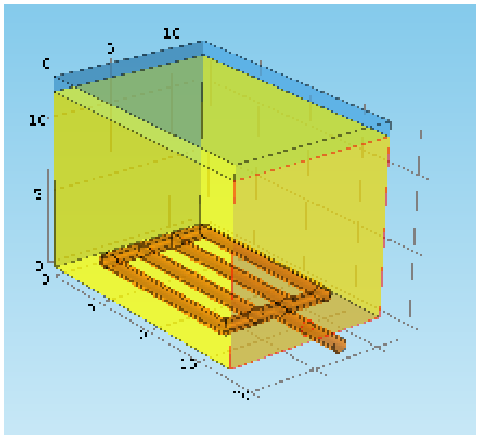

Figure 6. Schematic representation of mash tun reactor with four pipe manifold..

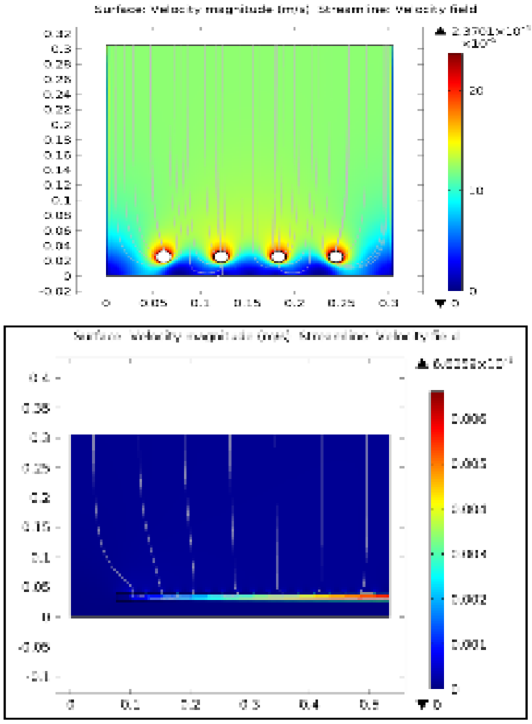

Figure 7. Computed streamlines for the x-y and x-z planes of the four pipe mash tun reactor.

Note that there is a large percentage of low-velocity regions in the y-z type model compared to the x-y type model. This is due to the lack of flow around the manifold legs in the y-z type model that is captured in the x-y models. The result is that the low flow in the region below the manifold is exaggerated in the y-z model. However, the area below the manifold still experiences relatively low flow in the x-y model, which meshes with actual experiences of home brewers. One of the primary sources of water lost when brewing comes from the percentage of water that remains trapped in the mash tun below the manifold and cannot be drained.

Table 1 summarizes the results of investigations of mash tun reactors with different number of pipes.

Table 1: Calculated efficiency and wort quality for one, four and eight pipe manifold mash tun reactors.

Pipes	Efficiency (%)	Oversparged (%)
1	89.9	45.8
4	91.2	42.4
8	88.4	28.5

According to these results, in terms of wort quality, the ideal mash tun design would include as many manifold legs as can possibly be fit into the mash tun. However, there is a slight drop in efficiency with high numbers of legs. Moreover, multiple pipe manifolds are more difficult to construct and maintain.

A detailed description of many other computational experiments performed and their results can be found in the Mr. Walsh's RPI Final Master's Project Report [5].

5. Conclusions

COMSOL Multiphysics provided a convenient and easy to use environment to carry out computer experiments designed to compare the effectiveness of various proposed mash tun reactor designs. Together with some basic empirical understanding of the brewing process, finite element modeling with COMSOL allowed the testing of ideas and intuition and helped generate insight and know-how useful to the home brewer.

6. References

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7. Acknowledgements

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