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# Energy efficiency improvement and fuel savings in water heaters using baffles

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## HIGHLIGHTS

- ▶ Thermal efficiency improved by simple/novel design of baffles inside water reservoir.
- ▶ Noticeable steady-state natural gas savings of about 5%.
- ▶ Extensive 3-D numerical investigations followed by experimental verifications.
- ▶ Baffle designs prototyped in identical water heaters for ANSI/US DOE test protocols.
- ▶ Numerical/experimental results verified thermal efficiency improvement & fuel savings.

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ABSTRACT

Thermal efficiency improvement of a water heater was investigated numerically and experimentally in response to presence of a baffle, particularly designed for modifying the flow field within the water reservoir and enhancing heat transfer extracted into the water tank. A residential natural gas-fired water heater was selected for modifying its water tank through introducing a baffle for lowering natural gas consumption by 5% as a target. Based on the geometric features of the selected water heater, three-dimensional models of the water heater subsections were developed. Upon detailed studies of flow and heat transfer in each subsection, various sub-models were integrated to a complete model of the water heater. Thermal performance of the selected water heater was investigated numerically using computational fluid dynamics analysis. Prior to baffle design process and in order to verify the developed model of the water heater, time-dependent numerically-predicted temperatures were compared to the experimentally-measured temperatures under the same conditions at six (6) different locations inside the water tank and good agreement was observed. Upon verifying the numerical model, the fluid flow and heat transfer patterns were characterized for the selected water heater. The overall design of the baffle and its location and orientation were finalized based on the numerical results and a set of parametric studies. Finally, two baffle designs were proposed, with the second design being an optimized version of the first design. The verified three-dimensional model of the water heater was modified to include the baffle designs and same thermal performance analysis was simulated confirming potential improvements in thermal efficiency. Thereafter, designed baffles were prototyped and assembled in identical water heater units and experiments were conducted according to standard water heater test procedures. Finally, numerical and experimental results verified thermal efficiency improvement in the water heater after introducing the baffles. As a result, baffle's second design is capable of lowering the natural gas consumption of the water heater by 4.95% under steady-state thermal efficiency test condition which meets the target of this research. However, the gas savings under actual usage patterns might be less than this value.



## 1. Introduction

Energy efficiency is crucially important in operation of heat exchangers and fuel-consuming devices and its improvement leads to fuel savings and environmental benefits of emission reduction. Baffles are flat or curved plates that are extensively used in various applications for stabilizing and directing flow, controlling sloshing or waves, overflow prevention, and mixing enhancement purposes [1,2]. Considering the coupling of velocity and temperature fields in fluids (through advection terms in the energy equation, natural convection and effects of turbulence), baffles can affect the temperature field and heat transfer as well. In other words, it is possible to utilize a baffle to manipulate the flow field so that it affects the temperature field by maximizing or minimizing heat transfer from/to the fluid. For instance, if the baffle increases heat transfer

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**Nomenclature**

| | |
|---|---|
| $C_p$ | specific heat, J kg$^{-1}$ K$^{-1}$ |
| $C_1$ | constant in the standard $k$–$\varepsilon$ turbulence model, equal to 1.44 |
| $C_2$ | constant in the standard $k$–$\varepsilon$ turbulence model, equal to 1.92 |
| $C_3$ | constant in the standard $k$–$\varepsilon$ turbulence model, equal to −0.33 |
| $C_\mu$ | turbulent viscosity constant, equal to 0.09 |
| $E$ | energy per unit mass, W kg$^{-1}$ |
| $G_b$ | generation of turbulent kinetic energy due to buoyancy, kg m$^{-1}$ s$^{-3}$ |
| $h$ | specific enthalpy, J kg$^{-1}$ |
| $HHV$ | higher heating value, J kg$^{-1}$ |
| $J$ | diffusion flux of species, kg m$^{-2}$ s$^{-1}$ |
| $K$ | thermal conductivity, W m$^{-1}$ K$^{-1}$ |
| $k$ | turbulent kinetic energy, m$^2$ s$^{-2}$ |
| $m$ | mass, kg |
| $p$ | pressure, N m$^{-2}$ |
| $Pr$ | Prandtl number |
| $u_i$ | time-averaged velocity components, m s$^{-1}$ |
| $u'_i$ | fluctuating components of velocity, m s$^{-1}$ |
| $S_h$ | volumetric heat source including heat release from chemical reactions, W m$^{-3}$ |
| $S_{ij}$ | rate of strain tensor, s$^{-1}$ |
| $T$ | temperature, K |
| $t$ | time, s |
| $x_i$ | Cartesian coordinates |

*Greek Symbols*

| | |
|---|---|
| $\alpha$ | thermal diffusivity, m$^2$ s$^{-1}$ |
| $\delta_{ij}$ | Kronecker delta |
| $\varepsilon$ | turbulent dissipation rate, m$^2$ s$^{-3}$ |
| $\eta$ | thermal efficiency |
| $\mu$ | dynamic viscosity, kg m$^{-1}$ s$^{-1}$ |
| $\rho$ | density, kg m$^{-3}$ |
| $\sigma_k$ | constant in the standard $k$–$\varepsilon$ turbulence model, equal to 1.0 |
| $\sigma_\varepsilon$ | constant in the standard $k$–$\varepsilon$ turbulence model, equal to 1.3 |
| $\tau$ | stress tensor, N m$^{-2}$ |
| $\tau_{ij}^R$ | Reynolds stress components, N m$^{-2}$ |

*Subscripts*

| | |
|---|---|
| $c$ | cold |
| $eff$ | effective quantities |
| $g$ | related to gas domain |
| $h$ | hot |
| $i, j, k$ | indices for tensor notation |
| mod | related to modified water heater using baffle in water tank |
| $s$ | related to solid domain |
| st | related to the selected water heater (standard base model) |
| $t$ | turbulent quantities |
| $w$ | related to water domain |

from combustion products to another fluid in a gas-fired heat exchanger, then the baffle is effective in thermal efficiency improvement. There are several cases reported in the literature showing that introduction of baffles can affect the heat transfer rate and temperature field in different applications such as heat exchangers, thermal regenerators, electronic cooling devices, autoclaves for crystal growth, internal cooling systems of gas turbine blades and cooling water jackets. Depending on the specific application, there are a wide variety of baffle shapes and configurations that affect heat transfer and flow patterns. The shape and orientation of these baffles depend on the geometry and flow characteristics of the specific application. Usually, heat transfer enhancement and control over the fluid flow velocity are the immediate results of utilizing baffles that has been studied and reported for different cases.

A primary academic study on this topic was reported by Berner et al. [3] who considered the effect of baffle presence in a shell and tube heat exchanger model using an approximate two-dimensional model. They simplified the problem by neglecting the interference of tubes with flow inside the shell to find the general characteristics of the flow (e.g. separation regions, circulation, stagnation points, boundary layers, pressure drop, flow pattern and periodicity). They used the Laser Doppler Anemometry (LDA) method in Plexiglas® and Pyrex®-glass channels with a total number of ten baffles connected to the top and bottom walls successively normal to the flow direction.

Kim and Anand [4] studied the periodically fully-developed turbulent flow and heat transfer between a series of conducting parallel plates with surface-mounted heat sources. Using a two-dimensional numerical model of the channel and plates and the $k$–$\varepsilon$ turbulence model, they found that presence of the plates (as baffles in electronic cooling channels) will directly affect the friction factor and the Nusselt number and will lead to an increase in heat transfer rate.

Dutta and Dutta [5] carried out an experimental and numerical investigation of friction loss and heat transfer of turbulent flow in a rectangular channel with constant heat flux on the upper wall with inclined baffles attached to it. They considered the effects of the baffle size, orientation and perforation on the average and local Nusselt numbers. They found that the size, positioning and orientation of the baffle has a significant influence on internal cooling heat transfer and using optimum size, positioning and orientation, heat transfer will be maximized. They also found an optimum perforation density for perforated baffles which leads to strong jet impingement phenomenon and maximizes heat transfer.

Another study on baffles was conducted by Chen et al. [6] who developed a mathematical model for three-dimensional numerical investigation of flow and heat transfer characteristics in cylindrical crystal growth systems. Modeling the raw material in the lower chamber as a porous layer, they found an upward-rising jet around the axis of the cylinder and a downward flow next to the wall of the upper chamber. The characteristics of the flow (and accordingly temperature field in the crystal growth zone) depended on the Grashof number, remaining laminar for low Grashof numbers, whereas changing to oscillatory or turbulent when the Grashof number was high. They found that using a baffle placed between the lower and upper chambers may reduce the flow strength but causes more uniform velocity and temperature distributions in the crystal growth zone (i.e. upper chamber). Finally, they found that putting a baffle between the two chambers clearly reduces the vertical velocity of upward-rising jet and produces a more uniform temperature distribution for crystal growth. Moreover, they emphasized that location, thickness, shape and porosity of the baffle can effectively influence the growth process and should be studied in detail.

An experimental study on the effect of porous baffles on heat transfer enhancement in channel flow was performed by Ko and Anand [7]. The intent of using porous baffles was to reduce the pressure drop and friction loss associated with the baffle's presence. They performed experiments on a rectangular channel with 14 successive porous baffles mounted on the top and bottom walls