CFD approximation in an Optical Fiber Trap

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References
The effects of light have been observed for hundreds of years, one clear example of that, are the observations of Kepler with respect to the comet tails pointing in the opposite direction to the sun. The radiation pressure from sunlight is an extremely small force $5\text{mN}/\text{m}^2$, but it becomes significant where gravity is negligible.

Following these observations we can take advantage of using concentrated beams of light to move small particles of diameters between 0.1 and 10 micras.
Optical trapping

Technique developed to capture, translate or manipulate microparticles.
Sketch of the arrangement

The model of the interaction of light with micro-particles for this case of study is shown in Fig. (1). In order to compare the simulation results with the experiments, just the interaction of the left fiber will be consider.

Figure: Forces due to reflection and refraction of light. Scattering Force and Gradient Force
Computational Fluid Dynamics (CFD) is a branch of fluid dynamics that applies computational methods and algorithms to analyze, describe or predict fluids behaviour.

How is CFD related to our task?

We present a first approach to study the behaviour of a fluid radiated by infrared light ($980\eta m$) in a single-mode optical fiber.

Example
CFD principle objective is solving conservation equations for all relevant parameters and variables. The conservation equations include the transport of the variable throughout the domain, as well as either its creation or its destruction. Conserved variables include mass, momentum, enthalpy, turbulent kinetic energy, turbulent energy dissipation rate, chemical species concentrations, amongst others.

The equation for conservation of mass, also termed the continuity equation, has the form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho U_i) = 0$$ \hspace{1cm} (1)

Where $\rho$ is the fluid density and $U_i$ is the fluid velocity in the $x_i$ direction.
The statement for the conservation of momentum is given by the **Navier-Stokes** equation:

$$\frac{\partial (\rho U_i)}{\partial t} + \frac{\partial}{\partial x_j} (\rho U_i U_j) = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3} \frac{\partial U_k}{\partial x_k} \delta_{ij} \right) \right] + \rho g_i + F_i$$

(2)

“The first term on the left side describes the variation of the fluid momentum in time; the second term describes the transport of the momentum in the flow (convective transport). The first term on the right hand side describes the effect of gradients in the pressure \( \rho \); the second term, the transport of momentum due to the molecular viscosity \( \mu \) (diffusive transport); the third term, the effect of gravity \( g \); and in the last term, \( F_i \) lumps together all other forces acting on the fluid.”
Equipment use for Experimental Part

- A pigtailed laser diode of 980nm, 200mW.
- Single-mode fiber (SMF-28-J9) with a nucleus diameter of 8.2µm, covering diameter of 125µm and Numeric Aperture of 0.14.
- Silica microspheres with a diameter of 5µm.
- Coccus-type bacteria of 10µm.
- The laser power at the fiber exit was 70mW.
Laboratory Setting

- Laser Diodes
- CCD Camera
- Lamp with output for OF
- Microscope
- Laser controllers
- Micropositioners
- OF

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Laboratory Setting
Parameters involve

For this simulation temperature and radiation pressure are calculated based on the Intensity delivered by a laser diode. The radiation pressure when there is total absorption is given by:

\[ P_r = \frac{I}{c} = \frac{F_r}{A} = \frac{P_w}{cA} \]  

(3)

Where the known parameters are, the output power of the fiber \( P_w = 70 \text{mw} \), the surface area of the sphere of the Coccus Bacteria (Radio=5\( \mu \text{m} \)). Substituting this data on Eq.3 gives a \( P_r = 0.7427 \)
To obtain the refraction index of the laser beam in water the numeric aperture is (NA=0.14) and the Snell Law are utilized with a refraction index of water of $\eta = 1.333$

$$\theta = \sin^{-1}\left(\frac{NA}{\eta}\right) \approx 6.0423$$  \hspace{1cm} (4)
3D Model

The geometry of the model for the 3D simulation is created in *Gambit 2.4.5*, the coordinates are generated to match the measures obtained in the experimental part. The program works creating faces to define volumes and generating meshes Fig. (2).

*Figure:* Gambit 3D solid with *Tet/Hybrid, TGrid* mesh for Coccus micro-particle and *Hex/Wedge, Cooper* mesh for the laser beam
In order to detail the study of the results, four planes were created:

1. Entrance
2. Exit
3. 0.5\(\mu\)m before and after the micro-particle.
4. 2 coplanar planes, one to the plane-xy and the other coplanar to plane-xz.
Effects observed

We have special interest in knowing how the radiation pressure affects the fluid and the silica particle. So we study two different positions for the silica at 50\(\mu m\) and at 30\(\mu m\) from the end of the fiber and analyze three factors:

1. Velocity Magnitude
2. Dynamic Pressure
3. Temperature
It is possible to represent the results obtained in different ways, in particular we simulated two positions for a silica particle at 50\(\mu m\) and at 30\(\mu m\):

1. **Velocity Vectors**: You can draw vectors in the entire domain, or on selected surfaces. By default, one vector is drawn at the center of each cell (or at the center of each facet of a data surface), with the length and color of the arrows representing the velocity magnitude.

2. **Contour Lines**: FLUENT allows you to plot contour lines or profiles superimposed on the physical domain. Contour lines are lines of constant magnitude for a selected variable (isotherms, isobars, etc.).
Velocity Vectors

(a) Spalart-Allmaras  
(b) K-Epsilon  
(c) K-Omega

**Figure:** Velocity Vectors Coloured by Velocity Magnitude (m/s) for a silica at 50µm from the end of the fiber using three different approaches
Figure: Contours of Dynamic Pressure (Pascal) for a silica at 30µm from the end of the fiber using three different approaches
Temperature

(a) Spalart-Allmaras  
(b) K-Epsilon  
(c) K-Omega

Figure: Velocity Vectors Coloured by Temperature (°K) for a silica at 50µm from the end of the fiber using three different approaches
The next step was to visualize the heat absorption and temperature distribution in different fluids.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Chemical Formula</th>
<th>Density (kg/m³)</th>
<th>Cp(J/kgK)</th>
<th>Thermal Conductivity (w/m-k)</th>
<th>Viscosity (kg/m·s)</th>
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</thead>
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<tr>
<td>Glycerin</td>
<td>c3h8o3</td>
<td>1259.9</td>
<td>2427</td>
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<td>4182</td>
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**Figure**: Fluids and Properties
Points

Three points were placed to take the temperature of the different fluids.

*Figure*: Location of the points
Values Obtained

Temperature values were:

- **Maximum** 450 K
- **Minimum** 300 K

![Temperature Values °K](image)

**Figure:** Temperatures measured at the three different points
Figure: Temperatures measured at the three different points
Figure: Graphic of the temperatures measured at the twelve different points
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Figure: Graphic of the temperatures of sodium sulfate measured at the twelve different points
Figure: Temperatures at the twelve different points for sodium sulfate
Figure: Graphic of the temperatures of silicon measured at the twelve different points
Figure: Temperatures at the twelve different points for silicon
Figure: Graphic of the temperatures of methil alcohol measured at the twelve different points
Methil Alcohol

Figure: Temperatures at the twelve different points for methil alcohol
Figure: Maximum and minimum temperatures measured for the different substances at the axis points and $\Delta T$. 

<table>
<thead>
<tr>
<th>Substance</th>
<th>Min Temperature</th>
<th>Max Temperature</th>
<th>Point 01</th>
<th>Point 02</th>
<th>Point 03</th>
<th>Point 04</th>
<th>Max $\Delta T$</th>
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<td>442</td>
<td>442</td>
<td>419</td>
<td>315</td>
<td>96</td>
</tr>
</tbody>
</table>
Figure: Temperatures measured for the different substances at the axis points
Figure: Maximum difference in the temperatures


Asier Elejalde Fernández et al., *Sistema de trampa de fibra óptica para espectroscopia raman*.


References III


References IV


Elizabeth M Marshall and André Bakker, *Technical notes tn144*.


THANK YOU QUESTIONS?