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Using This Manual

The Contents of This Manual

The FLUENT Magnetohydrodynamics (MHD) Module Manual tells you what you need to know to model magnetohydrodynamics with FLUENT. In this manual, you will find background information pertaining to the model, a theoretical discussion of the model used in FLUENT, and a description of using the model for your CFD simulations.

Typographical Conventions

Several typographical conventions are used in this manual’s text to facilitate your learning process.

• An informational icon (i) marks an important note.

• An warning icon (⚠️) marks a warning.

• Different type styles are used to indicate graphical user interface menu items and text interface menu items (e.g., Iso-Surface panel, surface/iso-surface command).

• The text interface type style is also used when illustrating exactly what appears on the screen or exactly what you need to type into a field in a panel. The information displayed on the screen is enclosed in a large box to distinguish it from the narrative text, and user inputs are often enclosed in smaller boxes.

• A mini flow chart is used to indicate the menu selections that lead you to a specific command or panel. For example,

  Define —> Boundary Conditions...

  indicates that the Boundary Conditions... menu item can be selected from the Define pull-down menu, and

  display —> grid

  indicates that the grid command is available in the display text menu.
The words before the arrows invoke menus (or submenus) and the arrows point from a specific menu toward the item you should select from that menu. In this manual, mini flow charts usually precede a description of a panel or command, or a screen illustration showing how to use the panel or command. They allow you to look up information about a command or panel and quickly determine how to access it without having to search the preceding material.

- The menu selections that will lead you to a particular panel are also indicated (usually within a paragraph) using a “/”. For example, **Define/Materials...** tells you to choose the **Materials...** menu item from the **Define** pull-down menu.

### Mathematical Conventions

- Where possible, vector quantities are displayed with a raised arrow (e.g., $\vec{a}$, $\vec{A}$). Boldfaced characters are reserved for vectors and matrices as they apply to linear algebra (e.g., the identity matrix, $\mathbf{I}$).

- The operator $\nabla$, referred to as grad, nabla, or del, represents the partial derivative of a quantity with respect to all directions in the chosen coordinate system. In Cartesian coordinates, $\nabla$ is defined to be

$$
\nabla = \frac{\partial}{\partial x} \hat{\imath} + \frac{\partial}{\partial y} \hat{\jmath} + \frac{\partial}{\partial z} \hat{k}
$$

$\nabla$ appears in several ways:

- The gradient of a scalar quantity is the vector whose components are the partial derivatives; for example,

$$
\nabla p = \frac{\partial p}{\partial x} \hat{\imath} + \frac{\partial p}{\partial y} \hat{\jmath} + \frac{\partial p}{\partial z} \hat{k}
$$

- The gradient of a vector quantity is a second-order tensor; for example, in Cartesian coordinates,

$$
\nabla(\vec{v}) = \left( \frac{\partial v_x}{\partial x} \hat{\imath} + \frac{\partial v_x}{\partial y} \hat{\jmath} + \frac{\partial v_x}{\partial z} \hat{k} \right) \left( v_x \hat{\imath} + v_y \hat{\jmath} + v_z \hat{k} \right)
$$

This tensor is usually written as

$$
\begin{bmatrix}
\frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\
\frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\
\frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z}
\end{bmatrix}
$$
– The divergence of a vector quantity, which is the inner product between $\nabla$ and a vector; for example,

$$\nabla \cdot \vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}$$

– The operator $\nabla \cdot \nabla$, which is usually written as $\nabla^2$ and is known as the Laplacian; for example,

$$\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}$$

$\nabla^2 T$ is different from the expression $(\nabla T)^2$, which is defined as

$$(\nabla T)^2 = \left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2$$

**Technical Support**

If you encounter difficulties while using FLUENT, please first refer to the section(s) of the manual containing information on the commands you are trying to use or the type of problem you are trying to solve. The product documentation is available from the online help on the documentation CD, or from the Fluent Inc. User Services Center (www.fluentusers.com).

If you encounter an error, please write down the exact error message that appeared and note as much information as you can about what you were doing in FLUENT. Then refer to the following resources available on the Fluent Inc. User Services Center (www.fluentusers.com):

- Installation and System FAQs - link available from the main page on the User Services Center. The FAQs can be searched by word or phrase, and are available for general installation questions as well as for products.

- Known defects for FLUENT - link available from the product page. The defects can be searched by word or phrase, and are listed by categories.

- Online Technical Support - link available from the main page on the User Services Center. From the Online Technical Support Portal page, there is a link to the Search Solutions & Request Support page, where the solutions can be searched by word or phrase.

The User Services Center also provides online forums, where you can discuss topics of mutual interest and share ideas and information with other Fluent users, and the ability to sign up for e-mail notifications on our latest product releases.
Contacting Technical Support

If none of the resources available on the User Services Center help in resolving the problem, or you have complex modeling projects, we invite you to call your support engineer for assistance. However, there are a few things that we encourage you to do before calling:

- Note what you are trying to accomplish with FLUENT.
- Note what you were doing when the problem or error occurred.
- Save a journal or transcript file of the FLUENT session in which the problem occurred. This is the best source that we can use to reproduce the problem and thereby help to identify the cause.
Introduction

Chapter 1.

The Magnetohydrodynamics (MHD) module is provided as an addon module with the standard FLUENT licensed software. A special license is required to use the MHD module.

Magnetohydrodynamics refers to the interaction between an applied electromagnetic field and a flowing, electrically-conductive fluid. The FLUENT MHD model allows you to analyze the behavior of electrically conducting fluid flow under the influence of constant (DC) or oscillating (AC) electromagnetic fields. The externally-imposed magnetic field may be generated either by selecting simple built-in functions or by importing a user-supplied data file. For multiphase flows, the MHD model is compatible with both the discrete phase model (DPM), the volume-of-fluid (VOF) and Eulerian mixture approaches in FLUENT, including the effects of a discrete phase on the electrical conductivity of the mixture.

This document describes the FLUENT MHD model. Chapter 2: Magnetohydrodynamic Model Theory provides theoretical background information. Chapter 3: Implementation summarizes the UDF-based software implementation. Instructions for getting started with the model are provided in Chapter 4: Using the FLUENT MHD Module. Appendix A: Guidelines For Using the FLUENT MHD Model provides a condensed overview on how to use the MHD model, while Appendix B: Definitions of the Magnetic Field contains definitions for the magnetic field, Appendix C: External Magnetic Field Data Format describes the external magnetic field data format, and Appendix D: MHD Module Text Commands lists the text commands in the MHD model.
Chapter 2. Magnetohydrodynamic Model Theory

This chapter presents an overview of the theory and the governing equations for the mathematical models used in FLUENT to predict flow in an electromagnetic field.

- Section 2.1: Introduction
- Section 2.2: Magnetic Induction Method
- Section 2.3: Electric Potential Method

2.1 Introduction

The coupling between the fluid flow field and the magnetic field can be understood on the basis of two fundamental effects: the induction of electric current due to the movement of conducting material in a magnetic field, and the effect of Lorentz force as the result of electric current and magnetic field interaction. In general, the induced electric current and the Lorentz force tend to oppose the mechanisms that create them. Movements that lead to electromagnetic induction are therefore systematically braked by the resulting Lorentz force. Electric induction can also occur in the presence of a time-varying magnetic field. The effect is the stirring of fluid movement by the Lorentz force.

Electromagnetic fields are described by Maxwell’s equations:

\[ \nabla \cdot \vec{B} = 0 \]  \hspace{1cm} (2.1-1)

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]  \hspace{1cm} (2.1-2)

\[ \nabla \cdot \vec{D} = q \]  \hspace{1cm} (2.1-3)

\[ \nabla \times \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t} \]  \hspace{1cm} (2.1-4)

where \( \vec{B} \) (Tesla) and \( \vec{E} \) (V/m) are the magnetic and electric fields, respectively, and \( \vec{H} \) and \( \vec{D} \) are the induction fields for the magnetic and electric fields, respectively. \( q \) (C/m\(^3\)) is the electric charge density, and \( \vec{j} \) (A/m\(^2\)) is the electric current density vector.
The induction fields $\vec{H}$ and $\vec{D}$ are defined as:

$$\vec{H} = \frac{1}{\mu} \vec{B} \quad (2.1-5)$$

$$\vec{D} = \varepsilon \vec{E} \quad (2.1-6)$$

where $\mu$ and $\varepsilon$ are the magnetic permeability and the electric permittivity, respectively. For sufficiently conducting media such as liquid metals, the electric charge density $q$ and the displacement current $\frac{\partial \vec{D}}{\partial t}$ are customarily neglected [1].

In studying the interaction between flow field and electromagnetic field, it is critical to know the current density $\vec{j}$ due to induction. Generally, two approaches may be used to evaluate the current density. One is through the solution of a magnetic induction equation; the other is through solving an electric potential equation.

### 2.2 Magnetic Induction Method

In the first approach, the magnetic induction equation is derived from Ohm’s law and Maxwell’s equation. The equation provides the coupling between the flow field and the magnetic field.

In general, Ohm’s law that defines the current density is given by:

$$\vec{j} = \sigma \vec{E} \quad (2.2-1)$$

where $\sigma$ is the electrical conductivity of the media. For fluid velocity field $\vec{U}$ in a magnetic field $\vec{B}$, Ohm’s law takes the form:

$$\vec{j} = \sigma(\vec{E} + \vec{U} \times \vec{B}) \quad (2.2-2)$$

From Ohm’s law and Maxwell’s equation, the induction equation can be derived as:

$$\frac{\partial \vec{B}}{\partial t} + (\vec{U} \cdot \nabla) \vec{B} = \frac{1}{\mu \sigma} \nabla^2 \vec{B} + (\vec{B} \cdot \nabla) \vec{U} \quad (2.2-3)$$

From the solved magnetic field $\vec{B}$, the current density $\vec{j}$ can be calculated using Ampere’s relation as:

$$\vec{j} = \frac{1}{\mu} \nabla \times \vec{B} \quad (2.2-4)$$
2.2 Magnetic Induction Method

Generally, the magnetic field \( \vec{B} \) in a MHD problem can be decomposed into the externally imposed field \( \vec{B}_0 \) and the induced field \( \vec{b} \) due to fluid motion. Only the induced field \( \vec{b} \) needs to be solved.

From Maxwell’s equations, the imposed field \( \vec{B}_0 \) satisfies the following equation:

\[
\nabla^2 \vec{B}_0 - \mu \sigma' \frac{\partial \vec{B}_0}{\partial t} = 0
\]

(2.2-5)

where \( \sigma' \) is the electrical conductivity of the media in which field \( \vec{B}_0 \) is generated. Two cases need to be considered.

2.2.1 Case 1: \( \vec{B}_0 \) Generated in Non-conducting Media

In this case the imposed field \( \vec{B}_0 \) satisfies the following conditions:

\[
\nabla \times \vec{B}_0 = 0
\]

(2.2-6)

\[
\nabla^2 \vec{B}_0 = 0
\]

(2.2-7)

With \( \vec{B} = \vec{B}_0 + \vec{b} \), the induction equation (Equation 2.2-3) can be written as:

\[
\frac{\partial \vec{b}}{\partial t} + (\vec{U} \cdot \nabla) \vec{b} = \frac{1}{\mu \sigma} \nabla^2 \vec{b} + ((\vec{B}_0 + \vec{b}) \cdot \nabla) \vec{U} - (\vec{U} \cdot \nabla) \vec{B}_0 - \frac{\partial \vec{B}_0}{\partial t}
\]

(2.2-8)

The current density is given by:

\[
\vec{j} = \frac{1}{\mu} \nabla \times \vec{b}
\]

(2.2-9)
2.2.2 Case 2: \( \vec{B}_0 \) Generated in Conducting Media

In this case the conditions given in Equations 2.2-6 and 2.2-7 are not true. Assuming that the electrical conductivity of the media in which field \( \vec{B}_0 \) is generated is the same as that of the flow, i.e. \( \sigma' = \sigma \), from Equations 2.2-3 and 2.2-5 the induction equation can be written as:

\[
\frac{\partial \vec{b}}{\partial t} + (\vec{U} \cdot \nabla) \vec{b} = \frac{1}{\mu \sigma} \nabla^2 \vec{b} + ((\vec{B}_0 + \vec{b}) \cdot \nabla)\vec{U} - (\vec{U} \cdot \nabla)\vec{B}_0
\]  

(2.2-10)

and the current density is given by:

\[
\vec{j} = \frac{1}{\mu} \nabla \times (\vec{B}_0 + \vec{b})
\]  

(2.2-11)

For the induction equation Equations 2.2-8 or 2.2-10, the boundary conditions for the induced field are given by:

\[
\vec{b} = \{b_n \quad b_{t1} \quad b_{t2}\}^T = \vec{b}^* 
\]  

(2.2-12)

where the subscripts denote the normal and tangential components of the field and \( \vec{b}^* \) is specified by the user. For an electrically insulating boundary, as \( j_n = 0 \) at the boundary, from Ampere’s relation one has \( b_{t1} = b_{t2} = 0 \) at the boundary.

2.3 Electric Potential Method

The second approach for the current density is to solve the electric potential equation and calculate the current density using Ohm’s law. In general, the electric field \( \vec{E} \) can be expressed as:

\[
\vec{E} = -\nabla \varphi - \frac{\partial \vec{A}}{\partial t}
\]  

(2.3-1)

where \( \varphi \) and \( \vec{A} \) are the scalar potential and the vector potential, respectively. For a static field and assuming \( \vec{b} \ll \vec{B}_0 \), Ohm’s law given in Equation 2.2-2 can be written as:

\[
\vec{j} = \sigma (-\nabla \varphi + (\vec{U} \times \vec{B}_0))
\]  

(2.3-2)
For sufficiently conducting media, the principle of conservation of electric charge gives:

\[ \nabla \cdot \vec{j} = 0 \quad (2.3-3) \]

The electric potential equation is thus given by:

\[ \nabla^2 \varphi = \nabla \cdot (\vec{U} \times \vec{B}_0) \quad (2.3-4) \]

The boundary condition for the electric potential \( \varphi \) is given by:

\[ \frac{\partial \varphi}{\partial n} = (\vec{U} \times \vec{B}_0)_{\text{boundary}} \cdot \vec{n} \quad (2.3-5) \]

for an insulating boundary, where \( \vec{n} \) is the unit vector normal to the boundary, and

\[ \varphi = \varphi_0 \quad (2.3-6) \]

for a conducting boundary, where \( \varphi_0 \) is the specified potential at the boundary. The current density can then be calculated from Equation 2.3-2.

With the knowledge of the induced electric current, the MHD coupling is achieved by introducing additional source terms to the fluid momentum equation and energy equation. For the fluid momentum equation, the additional source term is the Lorentz force given by:

\[ \vec{F} = \vec{j} \times \vec{B} \quad (2.3-7) \]

which has units of N/m³ in the SI system. For the energy equation, the additional source term is the Joule heating rate given by:

\[ Q = \frac{1}{\sigma} \vec{j} \cdot \vec{j} \quad (2.3-8) \]

which has units of W/m³.
For charged particles in an electromagnetic field, the Lorentz force acting on the particle is given by:

\[ \vec{F}_p = q(\vec{E} + \vec{v}_p \times \vec{B}) \]  

(2.3-9)

where \( q \) is the particle charge density (Coulomb/m\(^3\)) and \( \vec{v}_p \) is the particle velocity. The force \( \vec{F}_p \) has units of N/m\(^3\).

For multiphase flows, assuming that the electric surface current at the interface between phases can be ignored, the electric conductivity for the mixture is given by:

\[ \sigma_m = \sum_i \sigma_i \nu_i \]  

(2.3-10)

where \( \sigma_i \) and \( \nu_i \) are respectively the electric conductivity and volume fraction of phase \( i \). \( \sigma_m \) is used in solving the induction equations.
Chapter 3. Implementation

The MHD model is implemented using the user-defined functions (UDF) as a FLUENT add-on module, which is loaded into FLUENT at run-time. The model is accessed through a number of UDF schemes. The magnetic induction equation given by Equations 2.2-8 or 2.2-10 and the electric potential equation given by Equation 2.3-4 are solved through user-defined scalar (UDS) transport equations. Other model-related variables such as the external magnetic field data, current density, Lorentz force and Joule heat are stored as user-defined memory (UDM) variables. The MHD model setup and parameters are input using the MHD Model graphical user interface (GUI) panel and a set of text user interface (TUI) commands described in Chapter 4: Using the FLUENT MHD Module. Detailed information can be found in the following sections:

- Section 3.1: Solving Magnetic Induction and Electric Potential Equations
- Section 3.2: Calculation of MHD Variables
- Section 3.3: MHD Interaction with Fluid Flows
- Section 3.4: MHD Interaction with Discrete Phase Model
- Section 3.5: General User-Defined Functions

3.1 Solving Magnetic Induction and Electric Potential Equations

The magnetic induction equation and the electric potential equations are solved through user-defined scalar transport equations. For the magnetic induction equation a set of 2 or 3 scalar equations are solved, each representing a Cartesian component of the induced magnetic field vector in a 2-D or 3-D case. For the electric potential equation a single scalar equation is solved.

The convection and the diffusion terms of the scalar equations are defined using user functions DEFINE_UDS_FLUX(mhd_flux, ..., ns) and DEFINE_DIFFUSIVITY (mhd_magnetic_diffusivity, ..., ns) respectively. The user-defined scalar equation is identified by the scalar index ns.

The source terms to the induction equations and the potential equation are implemented using user function DEFINE_SOURCE(mhd_mag_source, ..., eqn) and DEFINE_SOURCE (mhd_phi_source, ..., eqn) respectively, where eqn identifies the scalar equations.
For unsteady cases, the additional unsteady source term is introduced through the user function `DEFINE UDS UNSTEADY(mhd_unsteady_source, ..., ns)`, where \(ns\) identifies the scalar being solved.

The induction and potential equations can also be solved in solid zones, in which case the fluid velocity terms in the equations are not considered. For multiphase flows, the MHD equations are solved in the mixture domain only.

The wall boundary conditions are implemented through user profile functions (`DEFINE PROFILE(mhd_bc...)`), and are applied to the Cartesian components of the induced magnetic field vector or to the electric potential. For external wall boundaries, three types of boundary conditions, i.e. electrically insulating, conducting and ‘thin wall’, can be applied. The ‘thin wall’ type boundary refers to an external wall where a 1-D magnetic or electric potential diffusion normal to the boundary is assumed, and the wall material and the thickness are specified for the boundary. For internal wall boundaries, that is the boundaries between fluid/solid or solid/solid zones, a coupled boundary condition is applied.

### 3.2 Calculation of MHD Variables

Apart from the Cartesian components of the magnetic field vectors and the electric potential function, which are stored as user-defined scalars, other MHD-related variables include the induced electric current density vector, induced electric field vector, the Lorentz force vector and Joule heat. These variables are stored in user-defined memory locations. Updating of MHD variables is accessed through the user function `DEFINE ADJUST(mhd_adjust, ...)`. The variables are updated at the start of each iteration using the solved induced magnetic field from the previous iteration.

### 3.3 MHD Interaction with Fluid Flows

Additional source terms due to the magnetic induction are added to the flow momentum and energy equations as user defined source terms. For the momentum equation, user function `DEFINE SOURCE(mhd_mom_source, ..., eqn)` is used to introduce the Lorentz force to the equation, where `eqn` identifies the Cartesian component of the fluid momentum. For the energy equation, the additional source due to Joule heating is added through user function `DEFINE SOURCE(mhd_energy_source, ..., eqn)`, where `eqn` is the energy equation index.
3.4 MHD Interaction with Discrete Phase Model

In discrete phase modelling, the Lorentz force acting on charged particles is introduced through the user function `DEFINE_DPM_BODY_FORCE(mhd_dpm_force, ...)`. User function `DEFINE_DPM_SOURCE(mhd_dpm_source, ...)` is used to update the volume fraction of the discrete phase inside a fluid cell and the volume-weighted electric conductivity of the discrete phase.

3.5 General User-Defined Functions

Several general UDFs are used as part of the MHD model implementation.

- `DEFINE_INIT(mhd_init, ...)` is an initialization function called during the general case initialization to set up the external magnetic field and initialize MHD model parameters and variables.

- `DEFINE_ADJUST(mhd_adjust, ...)` is called at the start of each iteration. It is used to adjust the magnetic boundary conditions and update MHD related variables and properties.
Chapter 4. Using the FLUENT MHD Module

This chapter provides basic instructions to install the magnetohydrodynamics (MHD) module and solve MHD problems in FLUENT. It assumes that you are already familiar with standard FLUENT features, including the user-defined function procedures described in the FLUENT UDF Manual. Appendix A: Guidelines For Using the FLUENT MHD Model also outlines the general procedure for using the MHD model. This chapter describes the following:

- Section 4.1: MHD Module Installation
- Section 4.2: Loading the MHD Module
- Section 4.3: MHD Model Setup
- Section 4.4: MHD Solution and Postprocessing
- Section 4.5: Limitations

4.1 MHD Module Installation

The MHD module is provided as an addon module with the standard FLUENT licensed software. A special license is required to use the MHD module. The module is installed with the standard installation of FLUENT in a directory called addons/mhd2.1 in your installation area. The MHD module consists of a UDF library and a pre-compiled scheme library, which needs to be loaded and activated before calculations can be performed.

4.2 Loading the MHD Module

The MHD module is loaded into FLUENT through the text user interface (TUI). The module can only be loaded when a valid FLUENT case file has been set or read. The text command to load the module is

```plaintext
define → models → addon-module.
```
A list of FLUENT addon modules is displayed:

FLUENT Addon Modules:
0. none
1. MHD Model
2. Fiber Model
3. PEM Fuel Cell Model
4. SOFC Fuel Cell Model
5. Population Balance Model
Enter Module Number: [1] 1

Select the MHD model by entering the module number 1. During the loading process a scheme library containing the graphical and text user interface, and a udf library containing a set of user defined functions are loaded into FLUENT. A message Addon Module: mhd2.1...loaded! is displayed at the end of the loading process.

The basic setup of the MHD model is performed automatically when the MHD module is loaded successfully. The setup includes:

- Selecting the default MHD method
- Allocating the required number of user-defined scalars and memory locations
- naming of:
  - User-defined scalars and memory locations
  - All UDF Hooks for MHD initialization and adjustment
  - MHD equation flux and unsteady terms
  - Source terms for the MHD equations
  - Additional source terms for the fluid momentum and energy equations
  - Default MHD boundary conditions for external and internal boundaries
  - A default set of model parameters
- DPM related functions are also set if the DPM option has been selected in the FLUENT case setup.

The MHD module setup is saved with the FLUENT case file. The module is loaded automatically when the case file is subsequently read into FLUENT. Note that in the saved case file, the MHD module is saved with the absolute path. Therefore, if the locations of the MHD module installation or the saved case file are changed, FLUENT will not be able to load the module when the case file is subsequently read.
To unload the previously saved MHD module library, use the

\[\text{Define} \rightarrow \text{User-Defined} \rightarrow \text{Functions} \rightarrow \text{Manage...}\]

menu and reload the module as described above. Note that the previously saved MHD model setup and parameters are preserved.

4.3 MHD Model Setup

Following the loading of the MHD module, you can access the MHD Model panel using

\[\text{Define} \rightarrow \text{Models} \rightarrow \text{MHD...}\]

or using the text command

\[\text{define} \rightarrow \text{models} \rightarrow \text{mhd-model}\]

Both the MHD GUI panel and TUI commands are designed for the following tasks:

- Enable/disable the MHD model.
- Select the MHD method.
- Apply an external magnetic field.
- Set boundary conditions.
- Set solution control parameters.

Operations of these tasks through the MHD Model panel are described in the following sections. The set of MHD text commands are listed in Appendix D: MHD Module Text Commands.

4.3.1 Enabling the MHD Model

If the MHD model is not enabled after the MHD module is loaded for the first time, you can enable it by clicking the Enable MHD button in the MHD Model panel, shown in Figure 4.3.1. The panel expands to its full size when the model is enabled, as shown in Figure 4.3.2.
Using the FLUENT MHD Module

Figure 4.3.1: Enabling the MHD Model Panel

Figure 4.3.2: The MHD Model Panel
4.3.2 Selecting an MHD Method

The method used for MHD calculation can be selected under MHD Method in the MHD Model panel. The two methods, Magnetic Induction and Electrical Potential, are described in Section 2.2: Magnetic Induction Method and Section 2.3: Electric Potential Method, respectively.

For the Magnetic Induction method, 2 or 3 user-defined scalars are allocated for the solution of the induced magnetic field in 2-D or 3-D cases. The scalars are listed as $B_x$, $B_y$ and $B_z$ representing the Cartesian components of the induced magnetic field vector. The unit for the scalar is Tesla.

For the Electrical Potential method, 1 user-defined scalar is solved for the electric potential field. The scalar is listed as $\varphi$ and has the unit of Volt.

Table 4.3.1 lists the user-defined scalars used by the two methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Scalar</th>
<th>Name</th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>Induction</td>
<td>Scalar-0</td>
<td>$B_x$</td>
<td>Tesla</td>
<td>X component of induced magnetic field ($b_x$)</td>
</tr>
<tr>
<td></td>
<td>Scalar-1</td>
<td>$B_y$</td>
<td>Tesla</td>
<td>Y component of induced magnetic field ($b_y$)</td>
</tr>
<tr>
<td></td>
<td>Scalar-2</td>
<td>$B_z$</td>
<td>Tesla</td>
<td>Z component of induced magnetic field ($b_z$)</td>
</tr>
<tr>
<td></td>
<td>(3-D)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potential</td>
<td>Scalar-0</td>
<td>Phi</td>
<td>Volt</td>
<td>Electric potential ($\varphi$)</td>
</tr>
</tbody>
</table>

4.3.3 Applying an External Magnetic Field

Application of an external magnetic field to the computation domain is done under the External Field $B_0$ tab in the MHD Model panel, as shown in Figure 4.3.3. Two $B_0$ Input Options are available for setting up the external magnetic field. One option is to Patch the computational domain with a constant (DC Field) and/or varying (AC Field) type. The other option is to Import the field data from a magnetic data file that you provide.

With the Patch option enabled, the AC field can be expressed as a function of time (specified by Frequency), and space (specified by wavelength, propagation direction and initial phase offset). The space components are set under the $B_0$ Component, as in Figure 4.3.3.
Figure 4.3.3: The MHD Model Panel for Patching an External Magnetic Field
You can also specify a Moving Field with a wave form that is either a sinusoidal or a square wave function (Figure 4.3.4). Definitions for the sinusoidal and square wave forms of patched magnetic fields are provided in Appendix B: Definitions of the Magnetic Field.

![MHD Model Panel](image)

Figure 4.3.4: The MHD Model Panel for Specifying a Moving Field

Selecting Import under the B0 Input Option in the MHD Model panel, as seen in Figure 4.3.5, will result in the import of magnetic field data. The data file name can be entered in the B0 Data File Name field, or selected from your computer file system using the Browse... button. Magnetic data can also be generated using a third-party program such as MAGNA. The required format of the magnetic field data file is given in Appendix C: External Magnetic Field Data Format.

When using the Import option, the B0 Data Media is either set to Non-Conducting or Conducting, depending on the assumptions used in generating the magnetic field data. (These choices correspond to “Case 1” and “Case 2”, respectively, as discussed in Section 2.2: Magnetic Induction Method.)
Figure 4.3.5: The MHD Model Panel for Importing an External Magnetic Field
The Field Type is determined by the field data from the data file. The choice of either the DC Field or the AC Field option in the panel is irrelevant if the import data is either DC or AC. However, selection of both options indicates that data of both field types are to be imported from the data file, and superimposed together to provide the final external field data. Make sure that the data file contains two sections for the required data. See Appendix C: External Magnetic Field Data Format for details on data file with two data sections.

The Apply External Field... button opens the Apply External B0 Field panel as shown in Figure 4.3.6. To apply the external field data to zones or regions in the computational domain, select the zone names or register names of marked regions from the panel and click the Apply button.

The Reset External Field button sets the external magnetic field variable to zero.

![Figure 4.3.6: Apply External B0 Field Panel](image)

### 4.3.4 Setting Up Boundary Conditions

Boundary conditions related to MHD calculations are set under the Boundary Condition tab in the MHD Model panel. Boundary conditions can be set to cell zones and wall boundaries.

For cell zones, only the associated material can be changed and its properties modified. Figure 4.3.7 shows the panel for cell zone boundary condition setup. The cell zone material can be selected from the Material Name drop-down list.
Figure 4.3.7: Cell Boundary Condition Setup
Note that the materials available in the list are set in the general FLUENT case setup. Please refer to the FLUENT User Guide for details on adding materials to a FLUENT case. The properties of the selected material can be modified in the Boundary Condition tab by clicking on the Edit... button to the right of the material name. This will open the Material panel, as shown in Figure 4.3.8. The material properties that may be modified include the electrical conductivity and magnetic permeability. The material electrical conductivity can be set as constant, a function of temperature in forms of piecewise-linear, piecewise-polynomial or polynomial, or as a user-defined function. The material magnetic permeability can only be set as a constant.

![Material Panel](image)

Figure 4.3.8: Editing Material Properties within Boundary Condition Setup

For wall boundaries, the boundary condition can be set as an Insulating Wall, Conducting Wall, Coupled Wall or Thin Wall. The panel for wall boundary condition setup is shown in Figure 4.3.9.

- The insulating wall is used for boundaries where there is no electric current going through the boundary.
- The conducting wall is used for boundaries that are perfect conductors.
- The coupled wall should be used for wall boundaries between solid/solid or solid/fluid zones where the MHD equations are solved.
- The thin wall type boundary can be used for external wall that has a finite electrical conductivity.

For conducting walls and thin wall boundaries, the wall material can be selected from the Material Name drop-down list, and its properties modified through the Material panel. A wall thickness needs to be specified for thin wall type boundaries.

If the Electric Potential method is selected, the conducting wall boundary is specified by either of Voltage or Current Density at the boundary, as shown in Figure 4.3.10.
Using the FLUENT MHD Module

Figure 4.3.9: Wall Boundary Condition Setup

Figure 4.3.10: Conducting Wall Boundary Conditions in Electrical Potential Method
4.3.5 Solution Controls

Under the Solution Control tab in the MHD Model panel, Figure 4.3.11, a number of parameters can be set that control the solution process in an MHD calculation. The MHD model can be initialized using the Initialize MHD button. When the DPM model is enabled in the FLUENT case setup, the related variables used in the MHD model can be initialized using the Initialize DPM button.

![Solution Control Tab in MHD Model Panel](image)

You have the option to enable or disable the Solve MHD Equation. When the Solve MHD Equation is enabled, you have the choice to Include Lorentz Force and or Include Joule Heating in the solution of flow momentum and energy equations. The underrelaxation factor for the MHD equations can also be set.

The strength of the imposed external magnetic field can be adjusted by specifying and applying scale factors to the external DC and/or AC magnetic field data.
4.4 MHD Solution and Postprocessing

4.4.1 MHD Model Initialization

Initialization of the MHD model involves setting the externally-imposed magnetic field and initializing all MHD related user-defined scalars and memory variables.

When a FLUENT case is initialized, all user-defined scalar and memory variables are set to zero. The external magnetic field data is set from the External Field B0 tab in the MHD Model panel. The Initialize MHD button under the Solution Control tab can be used to initialize the model during a FLUENT solution process. It is used when MHD effects are added to a fully or partially solved flow field, or when the model parameters are changed during an MHD calculation. It only clears the scalar variables and most of the memory locations used in the MHD model, the memory variables for the external magnetic field data are preserved.

4.4.2 Iteration

It is often an effective strategy to begin your MHD calculations using a previously-converged flow field solution. With this approach, the induction equations themselves are generally easy to converge. The underrelaxation factors for these equations can be set to 0.8 ∼ 0.9, although for very strong magnetic fields, smaller values may be needed. For the electric potential equation, the convergence is generally slow. However, the underrelaxation value for this equation should not be set to 1. As additional source terms are added to the momentum and energy equations, the underrelaxation factors for these equations should generally be reduced to improve the rate of convergence. In case of convergence difficulties, another helpful strategy is to use the B0 Scale Factor in the Solution Control tab (Figure 4.3.2). This will gradually increase the MHD effect to its actual magnitude through a series of restarts. When the strength of the externally imposed magnetic field is strong, it is advisable to start the calculation with a reduced strength external field by applying a small scale factor. When the calculation is approaching convergence the scale factor can be increased gradually until the required external field strength is reached.
4.4.3 Postprocessing

You can use the standard postprocessing facilities of FLUENT to display the MHD calculation results.

Contours of MHD variables can be displayed using the

Display → Contours...

menu. The MHD variables can be selected from the variable list.

Vectors of MHD variables, such as the magnetic field vector and current density vector, can be displayed using the

Display → Vectors...

menu. The vector fields of the MHD variables are listed in the Vectors Of drop-down list in the Vectors panel. Table 4.4.1 lists the MHD related vector fields.

Table 4.4.1: MHD Vectors

<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced-$\vec{B}$-Field</td>
<td>Tesla</td>
<td>Induced magnetic field vector</td>
</tr>
<tr>
<td>External-$\vec{B}$-Field</td>
<td>Tesla</td>
<td>Applied external magnetic field vector</td>
</tr>
<tr>
<td>Current-Density $\vec{J}$</td>
<td>A/m²</td>
<td>Induced current density field vector</td>
</tr>
<tr>
<td>Electric-Field $\vec{E}$</td>
<td>V/m</td>
<td>Electric field density vector</td>
</tr>
<tr>
<td>Lorentz-Force $\vec{F}$</td>
<td>N/m³</td>
<td>Lorentz force vector</td>
</tr>
</tbody>
</table>
4.5 Limitations

Many MHD applications involve the simultaneous use of other advanced FLUENT capabilities such as solidification, free surface modeling with the volume of fluid (VOF) approach, DPM, Eulerian multiphase, etc. You should consult the latest FLUENT documentation for the limitations that apply to those features. In addition, you should be aware of the following limitations of the MHD capability.

- As explained in Chapter 2: Magnetohydrodynamic Model Theory, the MHD module assumes a sufficiently conductive fluid so that the charge density and displacement current terms in Maxwell’s equations can be neglected. For marginally conductive fluids, this assumption may not be valid. More information about this simplification is available in the bibliography.

- For electromagnetic material properties, only constant isotropic models are available. Multiphase volume fractions are not dependent on temperature, species concentration, or field strength. However, sufficiently strong magnetic fields can cause the constant-permeability assumption to become invalid.

- You must specify the applied magnetic field directly. The alternative specification of an imposed electrical current is not supported.

- In the case of alternating-current (AC) magnetic fields, the capability has been designed for relatively low frequencies; explicit temporal resolution of each cycle is required. Although not a fundamental limitation, the computational expense of simulating high-frequency effects may become excessive due to small required time step size. Time-averaging methods to incorporate high-frequency MHD effects have not been implemented.
Appendix A. Guidelines For Using the FLUENT MHD Model

This appendix provides a basic outline for installing the magnetohydrodynamics (MHD) module and solving MHD problems in FLUENT.

While Chapter 4: Using the FLUENT MHD Module covers much of the same material in greater detail, this appendix presents a set of guidelines for solving typical MHD problems with FLUENT, with occasional references to Chapter 4: Using the FLUENT MHD Module where more information can be found.

A.1 Installing the MHD Module

Before using the MHD module, you first need to install the necessary files onto your computer. These files are provided with your standard installation of FLUENT. They can be found in your installation area in a directory called addons/mhd2.1. The MHD module is loaded into FLUENT through the text user interface (TUI)

\texttt{define\rightarrow models\rightarrow addon-module}

only after a valid FLUENT case file has been set or read.

Once the MHD model is installed, beneath the mhd directory there are two subdirectories: a lib directory, and a directory corresponding to your specific architecture, ntx86 for example. The lib directory holds a Scheme code called addon.bin that contains the MHD module graphical interface. The specific architecture directory, ntx86 for example, contains the following subdirectories that hold various FLUENT files:

2d 2ddp 3d 3ddp
2d_host 2ddp_host 3d_host 3ddp_host
2d_node 2ddp_node 3d_node 3ddp_node
A.2 An Overview of Using the MHD Module

To use the MHD module in a FLUENT simulation, follow the general guidelines:

1. Start FLUENT.
   To begin modeling your MHD simulation, you need to start an appropriate FLUENT session. Choose from either the 2d, 3d, 2ddp, 3ddp, or the parallel version of FLUENT.

2. Read in a mesh file or a case file.
   You can have FLUENT read in your mesh file, a previously saved non-MHD case file, or a previously saved MHD case file.

   Note that if you read in a new mesh file, you need to perform the appropriate grid check and grid scale procedures.

3. Load the MHD module.
   The MHD module is loaded into FLUENT using the text command
   ```
   define models -> add-on-module
   ```
   and entering the corresponding module number (Section 4.2: Loading the MHD Module).

4. Set up the MHD model.
   The MHD Model panel is accessed using the graphical user interface (GUI):
   ```
   Define -> Models -> MHD...
   ```
   If the MHD model is not enabled after the MHD module is loaded for the first time, you can enable it by clicking the Enable MHD button which will display the expanded panel (Section 4.3.1: Enabling the MHD Model).

5. Select an MHD method.
   The method used for the MHD calculation can be selected under MHD Method. The two methods are
   - Magnetic Induction (Section 2.2: Magnetic Induction Method)
   - Electrical Potential (Section 2.3: Electric Potential Method)

6. Apply an external magnetic field.
   This is done by entering values for the B0 components in the External Field B0 tab. B0 input options can either be
   - Patched, or
   - Imported
The **Field Type** will either be the **DC Field** or the **AC Field**. The **Field Type** is determined by the field data from the data file. Refer to Section 4.3.3: **Applying an External Magnetic Field** for details on applying an external magnetic field.

7. Set up the boundary conditions.

Under the **Boundary Condition** tab, cell zones and wall boundaries can be selected as well as the corresponding zone type.

Cell zone materials are selected from the **Material Name** drop-down list. The properties of the selected material can be modified by clicking on the **Edit...** button to the right of the material name. Note that the materials available in the list are set in the general **FLUENT** case setup


The material properties that may be modified include the electrical conductivity and magnetic permeability.

Wall boundary conditions can be set as an **Insulating Wall**, **Conducting Wall**, **Coupled Wall** or **Thin Wall** (see Section 4.3.4: **Setting Up Boundary Conditions**).

8. Set solution controls.

Under the **Solution Control** tab:

- The MHD equation is enabled or disabled.
- Lorentz force and Joule heat sources are enabled or disabled.
- Underrelaxation factors are set (reasonable underrelaxation factors for the MHD equations are 0.8 ~ 0.9).
- Scale factors can be used to adjust the strength of the imposed external magnetic field. As the calculation approaches convergence, the scale factor in the **Solution Control** tab can be increased gradually until the required external field strength is reached (Section 4.3.5: **Solution Controls**).
- The MHD model is initialized (Section 4.4.1: **MHD Model Initialization**).

9. Run the **FLUENT** MHD simulation.

Using the GUI

[**Solve**]→Iterate...

set the number of iterations. It is often an effective strategy to begin your MHD calculations using a previously-converged flow field solution. With this approach, the induction equations themselves are generally easy to converge. For more information, see Section 4.4.2: **Iteration**.

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10. Process the solution data.

You can use the standard postprocessing facilities of FLUENT to display the results of an MHD calculation. Contours of MHD variables can be displayed using the

\[\text{Display} \rightarrow \text{Contours}...\]

menu. The MHD variables can be selected from the variable list. Vectors of MHD variables, such as the magnetic field vector and current density vector, can be displayed using the

\[\text{Display} \rightarrow \text{Vectors}...\]

menu as custom vectors. For more information, see Section 4.4.3: Postprocessing.
Appendix B.  
Definitions of the Magnetic Field

B.1 Magnetic Field Definitions

The sinusoidal form of the magnetic field is defined as:

\[ B_0 = \vec{B}_0 + A_0 \cos(2\pi ft - K \cdot R + \phi) \]
\[ K = \frac{1}{\lambda} \left\{ \frac{1}{\cos \alpha} i + \frac{1}{\cos \beta} j + \frac{1}{\cos \gamma} k \right\} \]  
(B.1-1)

where \( \vec{B}_0 \) is the mean vector, \( A_0 \) is the amplitude vector, \( K \) is defined as the propagation vector, \( R \) is the position vector of an arbitrary point. \( \cos \alpha, \cos \beta \) and \( \cos \gamma \) are the \( x, y \) and \( z \) direction cosines respectively. The quantities \( f, \lambda, \) and \( \phi \) are the frequency, wavelength, and phase offset, respectively. For a non-moving field the propagation vector is zero. For a static field only applies.

The square form of the magnetic field is defined as:

\[ B_0 = \vec{B}_0 + A_0 \frac{\cos(2\pi ft - K \cdot R + \phi)}{|\cos(2\pi ft - K \cdot R + \phi)|} \]  
(B.1-2)

The definition of the propagation vector is the same as for the sinusoidal form.
Appendix C. External Magnetic Field Data Format

C.1 Magnetic Field Data Format

The external magnetic field data file is in text format and of the following structure:

```
MAG_DATA
nX nY nZ
X1 Xn
Y1 Yn
Z1 Zn
nAC Freq
BX_re−1 BY_re−1 BZ_re−1 BX_im−1 BY_im−1 BZ_im−1
...
BX_re−n BY_re−n BZ_re−n BX_im−n BY_im−n BZ_im−n
```

The first line is an identification tag for the data file. The second line defines the number of data points in the x, y and z directions. The next three lines define the ranges in x, y and z directions. The data points are assumed to be evenly distributed along each direction. Line 6 defines the AC field flag and frequency. When \( nAC = 0 \), the magnetic field is static. For AC field, \( nAC = 1 \) and \( Freq \) is the frequency in Hz.

The rest of the data file contains the magnetic field data points. Each line defines the components of the real and imaginary parts of the magnetic field vector on one data point. The data points are indexed as:

\[
l = i + nX((j - 1) + nY(k - 1))
\]

\[
i = 1, ..., nX; j = 1, ..., nY; k = 1, ..., nZ
\]

The data is listed in the ascending order from 1 to \( n \), where \( n \) is the total number of data points given by \( n = nX \ nY \ nZ \).

For magnetic fields comprised of both DC and AC fields, the entire file structure described above is repeated for the DC and AC parts. These two sections within the same file will be imported into FLUENT and stored separately. The order of the DC and AC sections of the file is not important.
The imported data is interpreted as a snapshot of the applied magnetic field at an instant in time. Complex form is used to accommodate oscillating/moving fields. Thus, using complex numbers, and with reference to the quantities defined in Appendix B: Definitions of the Magnetic Field,

\[
\vec{B}_0 \equiv \left\{ \begin{array}{c} BX_{re} \\ BY_{re} \\ BZ_{re} \end{array} \right\} + i \left\{ \begin{array}{c} BX_{im} \\ BY_{im} \\ BZ_{im} \end{array} \right\} \\
= \vec{B}_0 + A_0 \exp[i(2\pi ft + \phi)] \quad (C.1-1)
\]

For a DC field,

\[
\vec{B}_{0,i} = B_{re,i} \quad i = x, y, z \quad (C.1-2)
\]

For an AC field,

\[
A_{0,i} = \sqrt{B_{re,i}^2 + B_{im,i}^2} \quad i = x, y, z \quad (C.1-3)
\]

and

\[
\phi_i = \arctan\left( \frac{B_{im,i}}{B_{re,i}} \right) \quad i = x, y, z \quad (C.1-4)
\]

Note that when the external magnetic field import option is used, the frequency, \( f \), read from this file supercedes the value specified in the GUI.
mhd-models/ Define solver configuration.
  enable-mhd? Enable/disable MHD model.
  mhd-method Select MHD method.
boundary-conditions/ Define MHD boundary conditions
  list-zones List FLUENT zone information.
  fluid Set fluid zone boundary condition.
  solid Set solid zone boundary condition.
  wall Set wall boundary condition.

b0-scale-factor Set and apply external magnetic field scale factor.

external-b0-field Set and apply external magnetic field data.

initialize-mhd Initialize MHD model.

initialize-dpm Initialize DPM related MHD variables.

solution-control Set MHD solution control parameters.
Bibliography