A model for liquid metal electric current limiters

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Summary We present a simple model which describes the complex interplay between electromagnetic forces, inertia, and gravity in liquid metal current limiting devices utilizing the electromagnetic pinch effect. The dynamics of this system is described by a nonlinear differential equation for the fluid height. A bifurcation analysis of stationary states shows that for sufficiently high initial fluid levels the fluid height is a discontinuous function of the electrical current. The jump in fluid height above some critical current is accompanied by a strong increase of the total electric resistance of the system and results in the current limiting action of the device. An experimental study of the system confirms the predicted switching behavior. For low electric current the experiment is in quantitative agreement with the theory. Due to its conceptual and numerical simplicity our model enables us to isolate the pertinent parameters and scaling laws of liquid metal current limiters.

SUMMARY

When an electric current passes through an electrically conducting fluid, the interaction of the current with its own magnetic field produces a Lorentz force acting inwardly which can lead to an instability resulting in a reduction of the cross section of the fluid. This phenomenon, called pinch effect, has first been observed in a liquid metal in Northrup's classical experiment [1] and has since received considerable attention in plasma physics ([2] and references therein) as well as in liquid metal magnetohydrodynamics [3], [4].

Recently, the liquid metal pinch effect has found a new application in electrical engineering for current limiting devices in switchgear assemblies [5], [6]. Traditionally, a current limiter (e.g. a fuse) is a device which interrupts the electric current in a network in case of a short-circuit. After removal of the cause of the short-circuit the device has to be replaced or mechanically restored which may incur substantial expenditures, especially in industrial applications characterized by high electric power. In contrast, liquid metal current limiters exploit the pinch effect which reduces the cross section of the fluid and thereby leads to a drastic increase of the resistance via ignition of an electric arc. To effectively limit the maximum current this process has to be very fast (a few ms). An important advantage of a liquid metal current limiter is its "self healing" property. When the short circuit fault is removed, the system returns to its initial state without any external action. In spite of considerable progress in the design of such devices, the understanding of the underlying magnetohydrodynamic (MHD) phenomena is still far from complete. More specifically, no systematic theory is available to date that would be capable of describing the dependence of the critical electric current and of the response time on the geometry and other parameters of the system. Although full-scale numerical simulations of the coupled fluid-dynamic electromagnetic problem for realistic complex geometries provide useful insight, they fail to uncover the basic scaling laws of the system.

The purpose of the present work is to introduce a conceptually simple prototype problem for the current limiting action of the pinch effect in which the mathematical complexity of the governing three-dimensional time-dependent MHD-equations can be reduced to the greatest possible extent, while retaining the intricate interplay between electromagnetic, inertial and gravity forces, respectively. After the definition of our system and a qualitative discussion of its steady state behavior, we will formulate the mathematical model for the general time-dependent case. Further, we report results of a numerical bifurcation analysis supplemented by an analytical treatment in the vicinity of its critical point. We then describe a simple experiment in which we verify the predictions of our model. We finally summarize our conclusions and translate our findings into general scaling relations valid for a broad class of wall-bounded pinch effects under the influence of gravity forces.

References

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