Magnetohydrodynamics

Historical Evolution and Trends

by

S. MOLOKOV

Coventry University
UK

R. MOREAU

EPM-MADYLAM
St Martin d'Hères
France

and

H.K. MOFFATT

University of Cambridge
UK

Springer

Flow Control and Propulsion in Poor Conductors

Tom Weier, Victor Shatrov, and Gunter Gerbeth

Forschungszentrum Rossendorf, P.O. Box 510119, D-01314 Dresden, Germany
(T.Weier,V.Shatrov,G.Gerbeth)@fz-rossendorf.de

1 Introduction

The possibility to act on a fluid flow in a contactless way, offered by magnetohydrodynamics (MHD), stimulated the imagination of aerodynamists and naval engineers relatively early.

Ritchie [1] appears to be the first using electromagnetic forces to pump electrolytes in 1832. Figure 1 shows two of his apparatuses. Basically, the horizontal magnetic field component near the pole of a permanent magnet (N) interacts with the mainly vertical electric field between two ring electrodes (w, w′) to set the dilute acid in the angular gap (AB) into rotational motion.

In the 1950s, a multitude of aerospace applications of MHD flow control techniques has been envisioned using the fact that at high enough speeds air gets ionised by the action of shock waves and frictional heating, and thus becomes a conductor. Such high-speed conditions are typical for re-entry problems. Resler and Sears [2] and Busemann [3] proposed, among others, to use magnetic fields to control heat transfer, to decelerate or to accelerate vehicles, and to prevent flow separation. Although enthusiasm for the practical application of these ideas waned later on, the topic is now again under investigation in connection with scramjets, e.g., [4, 5], heat transfer mitigation [6] and electromagnetic braking for re-entry vehicles [7]. An overview of magnetoaerodynamic (MAD) research can be found in the proceedings of a recent von Kármán institute lecture series [8]. MAD deals with compressible fluids at hypersonic speeds, which represents quite a complex problem on its own, and will not be discussed here. Henceforth, the discussion is limited to incompressible fluids, mainly seawater. Due to the focus of our own work, the survey may be somewhat biased towards the boundary layer control (BLC).

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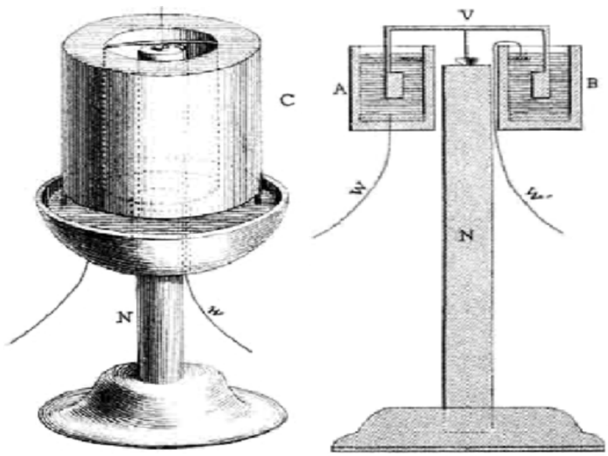

Fig. 1. Ritchie's electromagnetically rotated electrolyte columns [1]

2 Electromagnetic propulsion

Electromagnetic propulsion in seawater has been proposed by Rice [9] already in 1961. According to Friauf [10] and Way [11] the idea had attracted the attention of several inventors at that time. The main reason for this attraction has been the seemingly elegant operating principle using no moving parts. Proposed applications include the silent propulsion of naval submarines [12], the use in high-speed cargo submarines [11], and the propulsion of future high-speed surface ships without the danger of cavitation [13].

Conventionally (see, e.g., [11,14]), the electromagnetic propulsion methods are subdivided into four groups, as shown schematically in Fig. 2. If both the electric and magnetic fields are imposed, the propulsion scheme is termed "conductive" (Fig. 2a, c); if only an alternating magnetic field is applied, the method is referred to as "inductive" (Fig. 2b, d). The internal flow systems (Fig. 2a, b) use a duct with an electromagnetic pump, while the fields penetrate into the surrounding sea for external systems (Fig. 2c, d).

The arrangement of flush-mounted electrodes and magnets suggested by Rice [9], and shown in Fig. 3, belongs to category c, the external conductive propulsion. In 1966, Way [11] built a model submarine named EMS–1 with an electromagnetic thruster of the external conductive type at the University of California, Santa Barbara. The model was approximately 3 m long and had a displacement of approximately 400 kg. A dipole electromagnet provided a magnetic induction at the hull of 0.015 T. Powered by lead-acid batteries, the submarine reached a maximum velocity of approximately 0.8 knots (0.4 m/s).

This experiment even arrested the attention of mass media at that time. Nevertheless, in addition to the principal possibility to propel a marine vessel by the electromagnetic forces, some fundamental problems inherent in electromagnetic propulsion in seawater, already noted by Friauf [10] and Phillips [15],

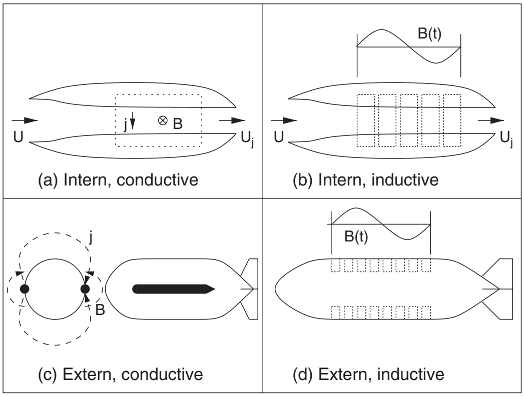

Fig. 2. Classification of electromagnetic propulsion methods according to Way [11]

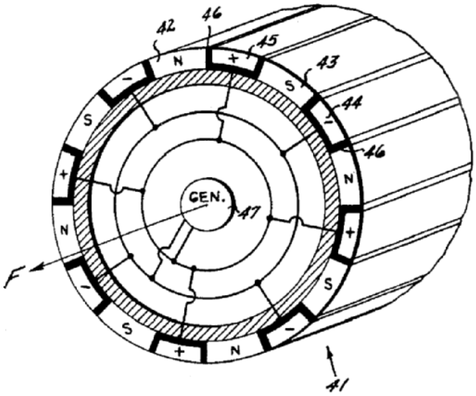

Fig. 3. Arrangement of electrodes (45) and permanent magnets (42) proposed by Rice [9] to propel a cylindrical body in seawater

were now demonstrated in practice. Especially, the unfavourable ratio of power input to available thrust was striking. After a period of active research, US activities in electromagnetic propulsion declined, apparently towards the end of the 1960s.

The reason for the efficiency deficit is easily explained. Regardless of the electromagnetic propulsion method, the Lorentz force density $\mathbf{f}$ producing the thrust is due to a current density $\mathbf{j}$ and a magnetic induction $\mathbf{B}$, namely

$$\mathbf{f} = \mathbf{j} \times \mathbf{B}. \quad (1)$$

Since in seawater applications the magnetic Reynolds number is small, the induced magnetic fields can be neglected and $\mathbf{B}$ becomes the applied field only. The current density is given by the Ohm's law

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{U} \times \mathbf{B}). \quad (2)$$

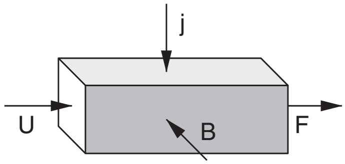

Fig. 4. Operating principle of an internal conductive propulsor

Here, $\mathbf{E}$ denotes the electric field strength, $\mathbf{U}$ the flow field, and σ the electric conductivity of the medium, respectively. Owing to its simplicity, internal conductive propulsion (type a) as sketched in Fig. 4 is chosen to illustrate the main performance criteria of electromagnetic propulsion in seawater following Thibault [16].

Of primary interest are the necessary power input to achieve a specific thrust (energy balance) and the total thrust available to propel the vessel at a specific velocity (momentum balance). The thrust per unit volume equals the Lorentz force density with the absolute value $f = jB$ $(f = |\mathbf{f}|, \ldots)$ in the case sketched in Fig. 4, assuming uniform and orthogonal electromagnetic and flow fields. The ideal electrical to mechanical efficiency η is the ratio of propulsive power or thrust per unit volume $p_T = jBU$ to the total power supplied per unit volume $p_E = jE$, where U denotes the flow velocity and E the electric field strength. This gives:

$$\eta = \frac{p_T}{p_E} = \frac{UB}{E} = \frac{1}{\phi}. \tag{3}$$

Thus, it appears that the ideal efficiency is the inverse of the load factor ϕ

$$\phi = \frac{E}{UB}, \tag{4}$$

giving the ratio of applied E to the induced UB electric field (see, e.g., [17]).

Expressing the current density in Eq. (1) by Ohm's law (2) and taking into account that the induced electric field acts against the applied one, the total electromagnetic thrust F can be expressed as follows:

$$F = \sigma U B^2 (\phi - 1) V. \tag{5}$$

Here V denotes the volume of the duct. Thus, for maximum ideal efficiency $(\eta = \phi = 1)$, the attainable thrust is zero. However, to propel a vessel, the usually non-zero total hydrodynamic drag D has to be balanced by the thrust. In a rough estimate, the total drag in turbulent flows is proportional to the square of the flow velocity: $D = kU^2$. Taking into account the relation $D = F$ and Eqs. (3), (5), it follows that the ideal electric efficiency is:

$$\eta = \frac{1}{1 + \frac{kU}{\sigma V B^2}}. \tag{6}$$

To maximise the efficiency at a given velocity U, the product VB^2 should therefore be chosen as large as possible. This has been realised quite early. Doragh, aware of the need for for high magnetic fields, suggested to use superconducting magnets already in 1963 [18].

Similar observations can be made for outer conductive propulsion methods (see, e.g., [11]), and for inductive methods (see, e.g., [15]). The main conclusion is always the need to deploy the highest possible magnetic induction in the largest available volume.

Inductive arrangements have been investigated, for example, by Phillips as early as 1962 [15] and later by Khonichev and Yakovlev [19], where the latter paper was the first one treating the coupled electromagnetic and hydrodynamic parts of the problem. Generally, the practical applicability of the inductive approach is limited by the fact that superconducting magnets providing an alternating magnetic field are not easily available. Therefore, the maximum magnetic field strength and consequently the efficiency are quite limited. However, Saji et al. [20] proposed and demonstrated experimentally an ingenious approach to the problem consisting in rotating the magnet including the cryostat. Unfortunately, the effort required in a real application might countervail the advantages gained. Intensive theoretical studies of the inductive approach have been performed by Yakovlev and co-workers in the late 1970s and early 1980s [21–23].

Saji and co-workers built two model ships, SEMD-1 and ST-500, with superconducting magnets with racetrack coils in the 1970s. In both cases, the propulsors were of the external conductive type. SEMD-1 [24] tested in 1976 [25] had a 0.6 m long and relatively bulky magnet with a maximum induction of ∼1 T mounted below the vessels hull. A maximum efficiency of 0.1% has been determined from tests in a tub, where the model was at rest and mounted to a force balance. In 1979, a second model ST-500 has been built and operated [25], now with a magnet of 2 T maximum induction and smoothly integrated into the hull of the vessel. In towing tank tests a maximum speed of 0.6 m/s has been reached with a total thrust of 15 N.

While thrusters of the external conductive type have been further investigated mainly numerically, e.g., [26–29], research concentrated on internal conductive propulsion in the 1980s and 1990s. This type has been favoured, because it allows for large thruster volumes with relatively homogeneous electromagnetic field distributions [16]. The most noticed achievement in this field has without doubt been the successful sea trial of the YAMATO-1 in 1992 [30], a 30 m long ship with 185 t displacement propelled by two electromagnetic thrusters with a mean induction of 4 T delivering 8,000 N of thrust each. YAMATO-1 reached top speed of 6.6 knots and a maximum electrical efficiency of 1.4% [30]. Considerably higher efficiencies have been reported for land-based experiments at Naval Undersea Warfare Center (NUWC) and Argonne National Laboratory (ANL) in the USA, where electromagnetic thrusters have been integrated in closed seawater loops. Meng et al. [31] found a maximum efficiency of ∼2.7% for a magnetic induction of 3.3 T and a load factor of $\phi \approx 20$. While the efficiency could be further increased to nearly 10% for a 6 T magnet at NUWC [32], as high values as 38% are reported by Meng et al. [32] for experiments with a 6 T magnet of 1 m bore diameter at ANL. However, this impressive device had a weight of more than 173 t.

For the simple crossed field arrangement sketched in Fig. 4 and used in a modified form for the thrusters of YAMATO-1 and in the experiments at NUWC and ANL, superconducting dipole magnets are necessary. These kind of magnets require massive structural enforcement to withstand the large magnetic forces, resulting in heavyweight constructions and relatively low maximum magnetic field strength.

For the same bore diameter, superconducting solenoids allow for lower weight and higher maximum field strength than dipole magnets. Recent thruster developments concentrated therefore on the use of solenoids. However, the axial magnetic field requires a special arrangement of electrodes and baffles forming the so called "helical thruster" (Fig. 5) as proposed and demonstrated by Bashkatov [33] as well as by Tada [34] in 1991.

However, the increase of electrical efficiency due to the higher magnetic field strength is accompanied by an increase of hydrodynamic losses in the thruster introduced by the baffle and other guiding plates. In 1995, Lin and Gilbert [12] used a 12 T helical thruster in a closed seawater loop and measured nearly 20% electrical efficiency. In 1998, Chinese researchers operated a 3.5 m long model ship HEMS-1 with 1 t displacement in a seawater pool [35, 36]. Equipped with a helical thruster with 5 T induction, a maximum speed of 0.68 m/s has been measured. In 1999, a helical thruster based on a 14 T solenoid has been run by a Chinese–Japanese group in a closed seawater loop [13, 37]. Ideal efficiencies exceeding 60% have been found, while the maximum efficiency including all losses is 13% for a load factor of 2.6 [37].

Meanwhile, worldwide activities in MHD-propulsion decreased, magnetic inductions and bore diameters of currently affordable superconducting magnets allow only for thruster efficiencies far below that of competing propulsion methods. This penalty currently outweighs all envisaged advantages. However, driven by the simplicity of the approach and the fascination it exerts on contemporary art, MHD-propulsion made its way into the classroom after all [38].

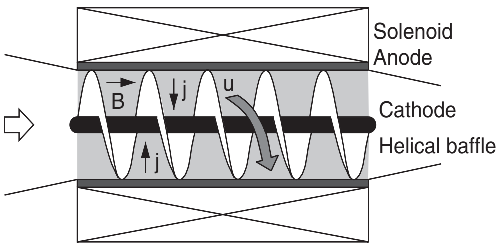

Fig. 5. Sketch of a helical thruster

3 Electromagnetic flow control

3.1 Drag reduction

Fluid dynamic drag can be of different origin. Electromagnetic flow control in seawater has mainly concentrated on the skin friction drag and to a lesser extent on the form drag. Wave drag has been dealt with by Petit [39] but while the demonstration experiment used a dilute acid, the focus of his work was on shock wave cancellation in hypersonic flight [40, 41]. The following discussion is limited to skin friction and form drag.

3.1.1 Transition delay

In 1961, Gailitis and Lielausis [42] proposed to use a stripwise arrangement of electrodes and magnets as sketched in Fig. 6 to delay the transition of a laminar boundary layer. Except for the plane geometry, electric and magnetic field sources are similar to the propulsion system patented by Rice [9] in the same year, see Fig. 3. However, the idea of Gailitis and Lielausis was not to propel the plate by the electromagnetic forces, but to compensate for the viscous losses of the near wall flow. For the electrode–magnet–arrangement in Fig. 6 the ratio of the electromagnetic to frictional forces, i.e., the Hartmann number Z, can be written as

$$Z = \frac{1}{8\pi}\frac{j_0 M_0 a^2}{\rho\nu U_\infty}. \tag{7}$$

Here M_0 denotes the magnetisation of the permanent magnets, j_0 the applied current density, a the width of the electrodes, ρ the fluids density, ν its kinematic viscosity, and U_∞ the outer flow velocity, respectively. For $Z = 1$, the growth of the boundary layer can be inhibited. Assuming the Lorentz force density distribution to be uniform in the spanwise direction and exponentially decaying with the distance y from the wall, an exponential distribution of the wall parallel velocity component u, namely

$$\frac{u}{U_\infty} = 1 - e^{-\frac{\pi}{a}y}, \tag{8}$$

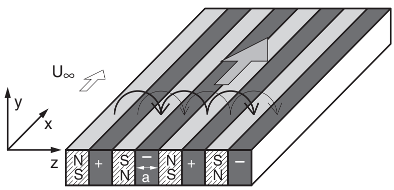

Fig. 6. Stripwise geometry of electrodes and magnets for a streamwise wall-parallel force as proposed by Gailitis and Lielausis [42]

follows as a solution of the boundary layer as well as the Navier–Stokes equations. The exponential boundary layer profile is similar to that of the asymptotic suction boundary layer and should therefore posses similar stability characteristics, i.e., a critical Reynolds number based on the displacement thickness of about $Re_{\delta_1 \mathrm{crit}} = 4.7 \times 10^4$ compared to only $Re_{\delta_1 \mathrm{crit}} = 520$ for the Blasius boundary layer [43]. The development of an exponential profile for a force distribution $f \sim \exp(-\pi y/a)$ and $Z = 1$ has been shown numerically by Tsinober and Shtern [44] by solving the boundary layer equations. Experimental work at that time has been limited to qualitative observations of flow cases considerably different from zero-pressure-gradient boundary layers [45]. Meanwhile, also experimental evidence is available. Figure 7 presents Laser–Doppler measurements showing convincingly the transformation of a Blasius boundary layer profile with $Re_{\delta_1} \approx 290$ to an exponential one [46].

Transition delay promises a huge potential for skin friction drag savings. Comparing typical laminar to turbulent skin friction drag, these savings may even be large enough to offset very low electrical efficiencies η (3). However, as is well known, linear stability of the asymptotic boundary layer profile alone is not a sufficient condition for the transition delay. In practice, many additional effects, e.g., receptivity to the disturbance environment and the influence of the real force distribution, have to be taken into account. So far, these aspects have only partially been addressed. The evolution of the boundary layer and the stability of the accompanying profiles has been studied by Zhilyaev et al. [47] and later by Albrecht et al. [48].

In 1962, Phillips [15] estimated power requirements for boundary layer stabilisation with induced fields and found them far exceeding possible savings.

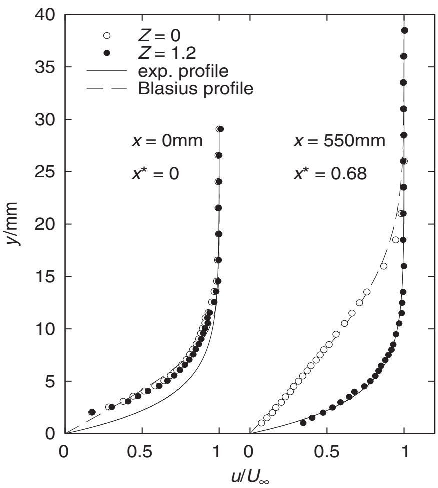

Fig. 7. Development of an exponential boundary layer profile under the influence of the Lorentz force

To the knowledge of the authors, for stabilisation purposes, Lorentz forces have up to now only be considered for modifications of the mean flow profile. Techniques acting on the disturbances (wave cancellation) offer potentially higher efficiencies, but are coupled to sophisticated sensor–actuator systems.

3.1.2 Turbulent boundary layers

Since transition control is practically limited to length Reynolds numbers $Re_x < 4 \times 10^7$ [49], techniques for skin friction reduction in turbulent boundary layers (TBL) are desirable in many cases. Though Shtern [50] discussed already in 1970 the possibility to limit the growth of a TBL by a streamwise Lorentz force, it was only at the beginning of the 1990s that electromagnetic control of TBLs became of increasing interest. While Meng [51] followed the ideas of [9] and the work on BLC in the 1960s reviewed by Tsinober [52] and Lielausis et al. [45], Nosenchuck and Brown developed a different approach based on wall normal forces in 1993 [53]. Especially the experiments by Nosenchuck and Brown [53], who coined the term electromagnetic turbulence control (EMTC) [54], were very well received at that time, e.g., [55], and sparked further research.

Mainly three different force configurations have been investigated in order to control TBLs: wall parallel streamwise (Fig. 6), wall parallel spanwise (Fig. 8, left), and nominally wall normal forces (Fig. 8, right).

Wall parallel forces in the streamwise direction have been applied, e.g., in the experiments of Henoch and Stace [56] and Weier et al. [57] as well as in the numerical analysis of Crawford and Karniadakis [58]. This force configuration increases instead of reducing wall shear stress, because the acceleration of the near wall fluid leads to a higher slope of the mean velocity profile in the streamwise direction. However, the momentum gain due to the Lorentz force surpasses the friction drag rise. While mean velocity and skin friction are increased near the wall, their fluctuating components are damped for higher momentum input [56,57]. Shtern's [50] concept of a TBL of constant thickness by means of streamwise forces has been experimentally verified in [57].

Nosenchuck and Brown [54], O'Sullivan and Biringen [59], Thibault and Rossi [60], and others used nominally wall normal, time-dependent forces. Nosenchuck and co-workers reported several successful experiments with a

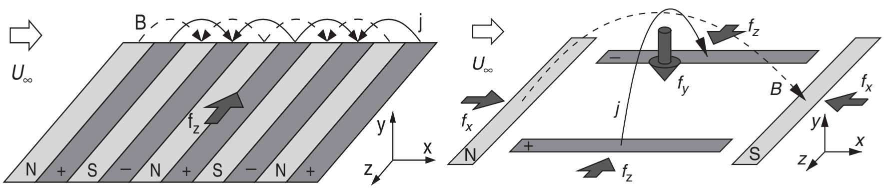

Fig. 8. Magnet/electrode arrangements for spanwise (*left*) and wall–normal forces (*right*)

multitude of electromagnetic actuators ("tiles") generating turbulent skin friction reductions of more than 90% [54], 55% [61], and a total drag decrease of more than 50% [62]. The physical mechanism behind this drag reduction is supposed to be a global reorganisation of the boundary layer into rotational periodic structures, cf. [63] and the sketches and flow visualisations in [64]. However, other groups were unable to reproduce these results [65]. As pointed out by Rossi and Thibault [66], the real force distribution produced by the electromagnetic tiles is quite complex and may play a crucial role in the experiments.

Time-dependent wall parallel forces in spanwise direction have been investigated numerically, among others, by Berger et al. [67], and Du et al. [65] and experimentally by Pang and Choi [68], and Breuer et al. [69]. Drag reductions ranging from 10% for the directly measured mean drag coefficient [69] to 40% for the local skin friction [68] have been found, indicating that this type of forcing is indeed able to reduce the skin friction drag of turbulent flows. The drag reduction mechanism is supposed to be similar to that suggested for spanwise oscillating walls [68]. Nevertheless, the energy balance of the approach is not favourable.

3.1.3 Form drag of bluff bodies

Compared to skin friction reduction, the use of Lorentz forces to control flow separation received less attention. Probably, the first experimental demonstration of separation prevention, as well as provocation, on the half-cylinder has been given by Crausse and Cachon [70].

Selected flow visualisations from their paper are reproduced in Fig. 9. Note that not all field sources are inside the body. Although Crausse and Cachon did not perform any force measurements, it is obvious from Fig. 9 that a

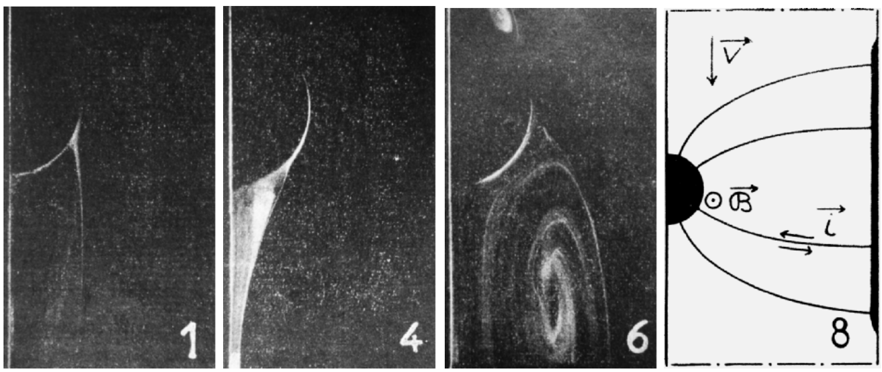

Fig. 9. Control of flow separating from the half-cylinder by the electromagnetic forces. (From [70].) Unforced flow (1), force downstream (4), force upstream (6), and the field configuration (8)

Lorentz force directed downstream reduces the size of the separation bubble behind the half-cylinder considerably, thereby reducing form drag as well. Similar experiments, but with an interchanged role of electric and magnetic fields and an additional conductivity gradient, where performed in 1961 by Lielausis [45, 71].

Successful electromagnetic control of the flow around a circular cylinder has been reported by Petit [39] for electrodes embedded in the cylinder and an externally applied magnetic field. A circular cylinder equipped with electrodes and permanent magnets generating a wall parallel force in the streamwise direction was used in the experiments and numerical calculations of Weier et al. [72]. Similar configurations have later been investigated by Kim and Lee [73], Posdziech and Grundmann [74], and Chen and Aubry [75]. While skin friction drag is increased by this force configuration, form drag is strongly reduced for an initially separated flow at Reynolds numbers Re of the order of 100. For stronger forcing the increase in skin friction drag dominates the form drag decrease. The total drag on the cylinder under these conditions is, however, negative due to the electromagnetically generated thrust.

Shatrov and Yakovlev [27] studied numerically the flow around a sphere with mainly wall parallel Lorentz force for Re up to 1,000. For increasing interaction parameter, i.e., the ratio of the electromagnetic to inertial forces, the size of the separation region is first reduced. Later, separation is suppressed completely resulting in a strong decrease of form drag. Skin friction drag is increased, as is always the case for streamwise wall parallel forces acting downstream. At sufficiently high interaction parameters, the sphere is driven upstream by the Lorentz forces. In a subsequent paper [76], Shatrov and Yakovlev extended the investigated Reynolds number range up to 10^5 treating the problem of a steady and axially averaged flow. For large Reynolds number, the total drag on the sphere was reduced four times, and despite the moderate electrical efficiency of $\eta \approx 40\%$, the total energy consumption was reduced as well. Note that this "moderate" electrical efficiency is high compared to what has been reached in MHD propulsion experiments, since low load factors at still sufficient momentum input, i.e., a strong magnetic field, is easier to realise numerically.

Very recently, Shatrov and Gerbeth [77] have shown that it is possible to reduce the drag on a sphere by three orders of magnitude using an optimised field distribution. Since a high load factor was assumed, efficiency of this drag reduction is nevertheless quite small.

3.2 Lift and manoeuvrability

Besides the drag reduction, there are other goals in flow control. A prominent one is the prevention of separation in order to generate a certain lift used for manoeuvring or stabilisation of marine vessels. For these applications, energetical efficiency is not always a primary goal. The emphasis is rather on the viability of a specific lift increase compared to the uncontrolled case.

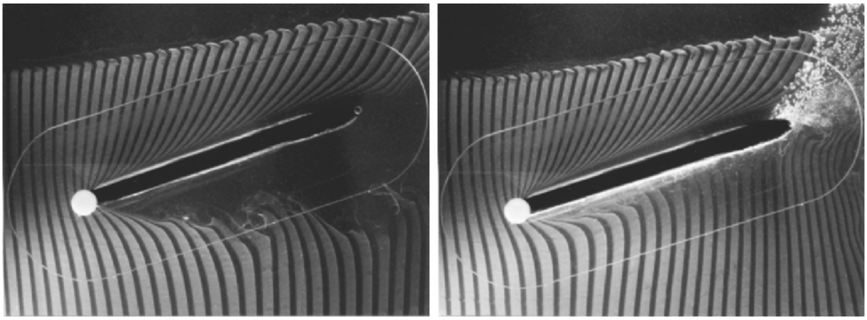

Fig. 10. Separated flow on the suction side of an inclined flat plate (*left*). Reattached flow due to a wall parallel streamwise Lorentz (*right*) [57]

Separation suppression at the suction side of inclined hydrofoils is, as in the case of bluff bodies, easily achieved by a streamwise wall parallel force acting in the flow direction. The flow visualisations in Fig. 10 demonstrate separation control in case of an 18° inclined flat plate at a chord length Reynolds number of $Re = 1.2 \times 10^4$. Electrodes and magnets are distributed practically along the whole chord length, leading to a uniform acceleration of the boundary layer flow along the plate.

The reattached flow shown in the right part of Fig. 10, while on one hand reducing the drag, on the other hand also re-establishes the lift of the plate. Figure 11 demonstrates this with measurements of the lift coefficient C_L on a PTL IV hydrofoil. At a fixed angle of attack of 17°, the suction side flow is already separated at the low chord length Reynolds numbers $3.4 \ldots 5.8 \times 10^4$. The Lorentz force influence is characterised by an electromagnetic momentum coefficient c_μ defined in analogy to the one used in separation control by blowing [80]. c_μ links the total electromagnetic momentum input to the dynamic pressure and has been shown by Weier et al. [78] to collapse separation control data of different experiments and enables a direct comparison to alternative control methods [81]. Two control regimes can be distinguished in Fig. 11: at small momentum coefficients, the boundary layer is gradually reattached to the foil's surface, a process leading to a steep increase in lift. Above a certain momentum coefficient $c_{\mu\mathrm{r}}$, necessary for complete reattachment, further lift increase can be observed which is weaker and is proportional to the square root of c_μ. These two regimes have been observed earlier in separation control by blowing, see the right part of Fig. 11, and termed BLC and "circulation control" by Poisson-Quinton [80].

Scale up of the experimental results reveal that power requirements for the original design based on conventional permanent magnets may prevent its application at sea going vessels.

In analogy to oscillatory suction and blowing [82], time-periodic Lorentz forces can be used to excite the separated flow. This indeed reduces the

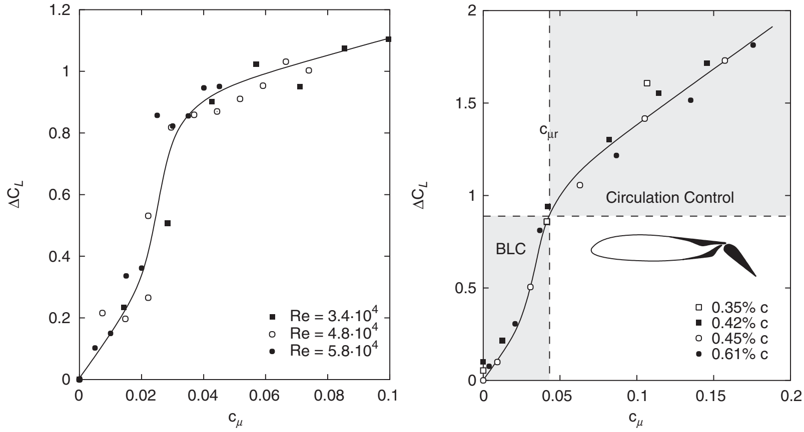

Fig. 11. Lift increase versus momentum coefficient for an electromagnetically controlled hydrofoil at 17° (*left*) [78] and for steady blowing over a 45° inclined flap on a NACA 23015 according to [79] and [80] (*right*)

momentum input necessary to recover the lift of the attached flow by more than an order of magnitude [81]. However, increasing the maximum lift requires momentum coefficients comparable to those necessary with steady electromagnetic forces. Despite this, electromagnetic forces have proven to be a flexible tool to study periodic excitation of separated flows. It has been shown, for example, that using different excitation wave forms, increases in the efficiency of 70% at constant efficient momentum input are possible [81].

4 Conclusions

Obviously the crux of the electromagnetic flow control, as well as the propulsion in poorly conducting fluids, is the efficiency limited by the achievable magnetic field strength. Among others, Busemann [3] realised similar fundamental problems concerning MAD already in 1961: *"Practically we are only at one tenth of the conductivity and one tenth of the magnetic field strength . . . "*. But at the same time he raised hopes that these unfavourable conditions might be overcome: *"The worst enemy of rigid mathematical proofs is the designing engineer, who accomplishes the 'impossible' by simply violating the assumptions of the proof."* For an energetically efficient electromagnetic propulsion or drag reduction, this engineer is yet to come. On the other hand, already today the electromagnetic force control might be of use for applications where the energetic balance is not the primary goal as described above for lift production.

Until this time arrives, practical applicability of electromagnetic forces for both propulsion as well as flow control, depends on the progress in readily available sources for high magnetic fields. At the same time dealing numerically with low load factors enforces the solution of coupled flow and electric fields as demonstrated by Shatrov and Gerbeth [83], a problem not unfamiliar to traditional MHD but gladly avoided in the majority of present papers on EMTC. In most of the works up to now, the electromagnetic flow control was applied using a few simple force configurations only. A key potential for optimisation lies in the tailoring of the electromagnetic forces, both in the spatial as well as in the time domain. An example for the spatial optimisation potential was recently given in [77]. The time optimisation of the acting Lorentz forces may eventually result in a reactive solution [49].

Regardless of the efficiency, Lorentz forces have attractive features to offer for basic research on flow control mechanisms. They are a unique possibility for an easily controllable momentum source of unlimited bandwidth and great flexibility.

The main problem for applications, namely efficiency, is different if one changes the point of interest to areas other than ship building. Current densities are an inherent feature of electrochemical processes, leaving only the skilful placements of magnetic sources to control momentum and thereby mass transfer, space–time–yield, etc. However, this is a topic on its own and is reviewed by Alemany and Chopart [84] in this volume.

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