Plasma Behaviour in the Floating Water Bridge and Biology

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Abstract

The behaviour of the Floating Water Bridge (FWB) appears to have similarities to the filamentary behaviour of Birkeland Currents in ionised-gas plasma. Plasma theory applied to the ions in the water of the FWB provides additional insights into aspects of the behaviour of the bridge which are as yet imperfectly understood by other analyses. Application of the same plasma principles to biological flows in plant roots and capillary blood flow may also offer insights into anomalous behaviour in these transport mechanisms also involving partially-ionised liquids.

Introduction

The anomalies in the behaviour of water are well known and have inspired a large amount of research designed to develop a full picture of water behaviour. Nevertheless, water is still not fully understood. Fuchs recently summed up the position:

> *"Much work has been done recently toward the simulation of liquid water, its intrinsic ions H^+ and OH^- and other ions in solution using ab initio electronic-structure methods, sometimes together with quantum dynamics methods, but still more work is called for in order to get a more complete and accurate picture of the liquid."* [Fuchs, 2010, p382]

In recent years, a considerable amount of research has been directed into the newly rediscovered phenomenon known as the Floating Water Bridge (FWB).

When a potential difference is applied between two beakers of pure water a small distance apart, a bridge of water forms between the beakers and remains stable while the potential difference is maintained. The beakers can even be separated by up to around 25mm without the bridge collapsing under its own weight or surface tension effects.

It is clear that the phenomenon depends on the applied electric field. What is not yet fully explained, despite the many investigations into the phenomenon, is exactly how the water interacts with the electric field.

This unusual behaviour of the FWB has prompted the following observations:

> *"The interaction of water with electric or magnetic fields also reveals many interesting aspects. The effect of magnetic fields seems extraordinary."* [Fuchs, 2010, p383];

and:

> *"…considering water as an electric ferrofluid subject to high electric fields allows for structures that are more than just a bit unusual…"* [Widom *et al*, 2009, p6]

Existing analyses of the phenomenon can model many individual aspects of this unusual behaviour in a FWB but no one theory can yet explain all the observations.

As Fuchs concluded in 2010:

> *"However, [the FWB's] final stage—a macroscopic, rotating cylinder with special optical properties through which two water currents run—still represents an interesting opportunity to further study and learn about the interactions of water with electric fields."* [Fuchs, 2010, p400]

Some behaviour of biological systems is equally puzzling. For example, Steudle observed:

> *"During root development, the axial resistance [of flows] in onion was reduced by three orders of magnitude. The differences between measured and calculated values of axial hydraulic resistances are known from the literature."* [Steudle, 1994, p83]

Recently, Pollack has demonstrated that water in biological systems becomes structured and negatively charged adjacent to hydrophilic surfaces. In very recent work, his team has also shown that tubes and tunnels formed of hydrophilic materials and immersed in water generate 'unexpected axial flows' without any apparent external driving force. [Yu *et al*, 2011 p1 &ff]

Common factors between biological tubes and the FWB are that both transport partially ionized liquids in thin cylindrical tubes and both seem to involve transport of electric charge. This suggests that an interdisciplinary approach involving transport of electric current in plasma may offer further insights into the behaviour of the FWB and biological systems.

What follows is an initial attempt to apply the principles of plasma Birkeland Currents to the filament of water in a FWB. The insights arising from this analysis are then applied to transport in biological tubes containing structured water layers.

Summary of the Characteristics of the Final Stage of the FWB

The known characteristics of the final stage of the FWB can be summarized for present purposes as follows:

1. A stable nearly cylindrical tube of water of 1-2 mm diameter extending up to 25mm between two beakers of pure water under the influence of a large (15kV) applied electric potential difference [Fuchs *et al*, 2008, p2]
2. Very slight catenary bowing under the gravitational force, indicative of enhanced stiffness of the FWB and/or significant tension in the bridge preventing further sagging. The sag remains constant as the filament diameter increases. [Fuchs *et al*, 2008, p2]
3. A macroscopic, rotating cylinder with special optical properties through which two water currents run. [Fuchs, 2010, p4]
4. An inner core distinct from an outer annular layer. [Fuchs *et al*, 2008, p3]
5. Charge transport across the bridge; the anode beaker acquires a larger net +ve charge. [Fuchs, 2010, p399 & Fig. 16]
6. Equality of final water flows in the forward and backward directions which prevents the cathodic beaker overflowing despite initial net inflow during the early development stages of the bridge [Fuchs, 2010, p397]
7. Very fast (0.1 – 0.3 m/s [Fuchs *et al*, 2007,p3]) rotation of the outer tubular layer, clockwise when viewed towards the cathode [Fuchs, 2010, p396]
8. Apparent (but unconfirmed) concentration of positive charge in the outer, rotating, layer and negative charge in the inner layer. [Fuchs, 2010, p395]
9. Water rheology similar to a ferrofluid; alignment of coherent domains under the influence of the applied electric field [Widom *et al*, 2009, p6]
10. Occurrence of dynamic zones of different density, possibly attributable to the formation of nanobubbles in the fluid. [Fuchs, 2010, p394]
11. Polarisation of the molecules in the rotating outer shell under the influence of the electric field. [Fuchs, 2010, p396]
12. Rupturing of the FWB tends to be explosive, in the nature of a whiplash, due to the release of constraining forces. [Fuchs *et al*, 2008, p4]

Existing Analyses of the FWB

Researchers have approached the analysis of the FWB from both the classical (EHD) and quantum (QED) directions.

The classical approach has wide-ranging industrial applications in electro-wetting and electrophoresis techniques where the behaviour of the fluids is well understood in EHD terms. However, when applied to the FWB, there appear to be some anomalies with this approach.

The original classical electrohydrodynamic equations for a leaky dielectric cylinder under an axial electric field were published by Melcher and Taylor in 1969. The essence of the M-T model is that a small amount of free charge at the surface is enough to set the liquid into motion [axially] with velocities up to a few mm/s [Marin & Lohseb, 2010, p8] Also, electrodynamic currents are assumed to be so small that magnetic induction effects can be ignored. [Melcher & Taylor, 1969, p111]

The model was completed in 1997 by Saville, who postulated a stability condition for fluid cylinders subject to high axial electric field strengths. [Saville, *1997*]

Burcham and Saville [2002] extended the earlier work and applied the Taylor-Melcher theory to a vertical liquid bridge suspended in a dielectric gas. Their conclusions were that the model needed an arbitrarily adjustable additional parameter in order to make the theory agree with experimental results. The authors state:

> *"… although the quantitative agreement between theory and experiment for the cylinder–amphora transition is not as close as one might like, using surface transport as an adjustable parameter brings theory and experiment into agreement. However, this entails introducing a property that was not measured in the experimental study. Indeed, it is not clear how this measurement should be made. Nevertheless, the theory shows that bridge stability is acutely sensitive to surface transport."* [Burcham & Saville, 2002, p181, pdf p19]

Surface transport depends on surface conductivity. The authors had previously speculated as to the possible causes of variation in this parameter:

> *"While one expects the surface conductivities at the two aspect ratios to be closer to one another, it should be noted that only small amounts of electrolyte are needed to produce conductivities of this magnitude. Contamination may also be a factor. Another possibility is that the density of ions in the surface is field dependent."* [Burcham & Saville, 2002, p180]

The same authors had studied bridges in low-gravity situations in 1999. The results had not been entirely as expected. They concluded that report:

> "*Several observations conflict with what is expected with leaky dielectric liquids"* including *Unexpected differences between the behaviour of liquids with different conductivities…. At present we have no ready explanation for this behaviour.* [Burcham & Saville, 2002, *pp 54-55]*

Widom *et al*. analysed the water bridge tension terms of the Maxwell pressure tensor in a dielectric fluid. [Fuchs, 2010, p 388] They concluded that "*The resulting tension in the water bridge sustains a siphon between two beakers"* and which, they conclude, behaves as a Bernoulli flow between the two beakers, oscillating at around 5Hz. [Widom *et al*, 2009, p6]

Widom *et al*'s analysis assumed de-ionised water throughout. They state:

> *"The need for de-ionized water in the experiment is evidently due prohibiting conductivity effects from masking the insulating dielectric effects."* [Fuchs *et al*, 2011 *p1]*

However, the presence of charge in the beakers after a FWB experiment suggests that Widom's analysis is incomplete despite its apparently 'satisfactory' agreement with observed catenary sagging. In fact, the observed conductivity effects would apparently mask the dielectric effects and so cast doubt on the Widom analysis.

These and other observations may have prompted, Del Giudice *et al* [2010] to suggest in 2010 that the EHD approach has limitations:

> *"… present* [EHD] *theories have difficulties explaining more than a few of [water's] properties at once, and no theory so far could satisfyingly explain one lately rediscovered phenomenon, the floating water bridge."* [Del Giudice, Fuchs & Vitiello, 2010 *p9]*

They argue instead that "*The QED approach to this phenomenon provides a possible theoretical background for many of the bridge's features"* [Del Giudice, Fuchs & Vitiello, 2010, *p 9]*

Fuchs [2010] summarised the early quantum approaches as follows:

> *"From a quantum mechanical point of view, density functional theory indicates that an electric field would stretch the intermolecular hydrogen bonds in the water network, eventually breaking the three dimensional morphologies to form linear, branched, or netlike structures, resulting in dipolar water monomers aligning along the field axis which coincides with the water bridge axis."* [Fuchs, 2010, pp388/9]

Rai *et al* describe the molecular mechanism:

> *"Summarizing the structural evolution* [of chains from clusters], *one may view the effects as if the applied field smoothens out the 3D morphologies of water clusters to form a linear, branched, or netlike structure by reorienting the water molecules along the field lines."* [Rai *et al*, 2008 p8]

But Fuchs offers a caution:

> *"However, the calculated field strength necessary in order to achieve such chains could are considerably higher than the ones applied in the water bridge experiment."* [Fuchs, 2010, pp388/9]

Fuchs goes on to suggest that quantum field theory (QFT) can explain many features of the water bridge. In particular, QM coupling can form coherent domains in water in which all the molecules oscillate in phase. Application of an external electric field tends to align these coherent domains to form super-domains, thereby leading to Widom' analogy of water as an "electric ferrofluid". [Fuchs, 2010, pp 389- 390]

Fuchs summarises:

> *"When addressing the properties of the water bridge, QFT can predict many of its features, such as … the stability of the bridge due to the formation of super-domains …* [Fuchs, 2010,p391]

Nevertheless, despite the partial successes of the QFT approach, we saw above that Fuchs concluded in the same paper that:

> *"However, [the FWB's] final stage—a macroscopic, rotating cylinder with special optical properties through which two water currents run—still represents an interesting opportunity to further study and learn about the interactions of water with electric fields."* [Fuchs, 2010, p400]

It is that final stage of the FWB that seems to have eluded a full description by either EHD or quantum approaches. The key elements that remain to be fully explained include:

- annulus and core cylindrical structure;
- simultaneous bi-directional flows of water; and
- rotation of the annular layer

We have made reference above to the prime importance of electromagnetic effects in the behaviour of the FWB. We will therefore compare the FWB with another filamentary structure in which electromagnetic effects dominate the behaviour.

The Behaviour of a Plasma Birkeland Current

Plasma is the fourth state of matter and is now known to be the most common state of matter in the Universe outside Earth's biosphere. [Rogoff, 1991, extract] Plasma is sometimes described as an ionised gas. This is technically true but does not reflect the complexity of the behaviour of plasma under the influence of the electromagnetic forces inherent within it.

One common pattern of behaviour unique to plasma is the ability to transmit filamentary electrical currents through the surrounding plasma without affecting it. The plasma rearranges itself to form what is effectively an insulated cable around the current path.

It does this by forming a cylindrical double layer or sheath on the outside of the axial current filament. The double layer consists of adjacent cylindrical layers of positive and negative charge. Together, these generate a radial electric field which ensures no net current across the double layer. [Peratt, 5.5.1]

The filamentary arrangement is known as a Birkeland Current (BC).

The zone within the sheath is also governed by Maxwell's Equations and the Lorentz Force Law applied to the individual charged particles in the filament, as explained further by reference to Figure 1.

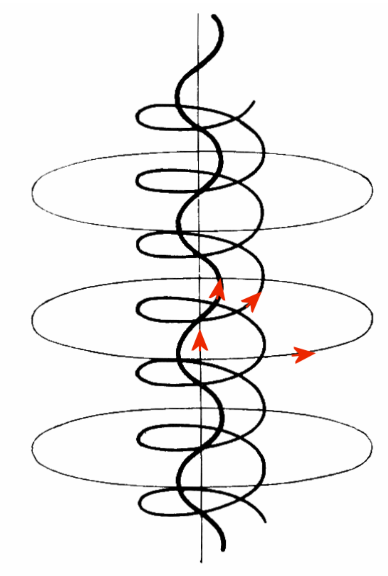

Figure 1. Magnetic Field Lines in a Birkeland Current [After Peratt Fig. 4.28]

The external field B_z is vertically upwards in the figure. Three separate magnetic field lines resulting from the interaction of a current I_z flowing under the influence of an electric field E_z are shown. The degree of helicity of the net magnetic field lines is radially dependent. Due to the **I** x **B** vector cross product, the charge carriers (current) are constrained to follow the net magnetic field lines at any given radius.

According to Peratt [4.6.3], the net result of the interaction of the Lorentz Force and the electromagnetic fields generated by the moving particles themselves is a spiralling filamentary pattern in which the circularity of the paths of the particles is dependent on their radial distance from the axis of the filament.

In this magnetic field pattern, any current element which is slightly misaligned with the magnetic field in its locality will experience a radial Lorentz force which will shift the current element towards or away from the axis to a zone with greater or lesser degree of helicity. This automatically happens in such as way to ensure that the two vectors are re-aligned.

This gives rise to the alternative nomenclature for a Birkeland Current as a "Field-aligned Current" in which the **I x B** vector cross-product disappears and the arrangement is free of Lorentz forces.

The force-free configuration represents a minimum-energy state [Peratt, 1992, p29] and therefore it has inherent stability. The outer azimuthal (ring) magnetic field generated principally by the inner axial core of current effectively acts to constrain the filament and minor lateral disturbances are restored by the field forces.

Peratt says of the force-free configuration in a Birkeland Current:

> *"It proves the stability of force-free fields and shows that in a system in which the magnetic forces are dominant and in which there is a mechanism to dissipate the fluid motion, force-free fields .. are the natural end configuration."* [Peratt, 1992, *p29, s1.7.2]*

It is also the most efficient direction for current to travel in through a magnetic field. The Lorentz Force Law effectively imposes an electrical resistance on motion transverse to the magnetic field by acting on particles moving in that direction due to the Lorentz Force. The resistance is therefore lowest in the direction parallel to the magnetic field lines where the Lorentz Force is absent.

One other effect is also relevant to this paper.

The outer layers of the filament follow the more helical paths, which effectively imposes a spiralling rotation on the flow of particles. Because most of the current in a plasma is carried by the electrons, the azimuthal flow component amounts to a net azimuthal current which will increase the axial magnetic field due to solenoid action.

Comparison of the Characteristics of a Birkeland Current in Plasma and the FWB

Obvious similarities between the characteristics of a Birkeland Current in plasma and the FWB include the following:

- Filamentary cylindrical structure.
- Applied axial electric field and resulting axial current. In both cases, an external driving electric field generates an axial current along the filament.
- Helical motion of outer layer compared to the inner layer.
- A radial electric field. According to Armstrong, [quoted in Fuchs, 2010, p394],the FWB has a positively-charged outer layer and negative core; a BC has a confining Double Layer. In both cases, a radial electric field is formed.
- Bi-directional transport. The FWB, in its final stable form, has equal flow rates in both directions. Current in a BC is carried by both ions and electrons, which flow in opposite directions.

Discussion of the Final Form of the FWB with Reference to BC Dynamics

In the final, stable, situation, mass transport of water occurs simultaneously in both directions.

> *"The water bridge reveals a multilayered structure with mass transport mainly [initially] from the anode to the cathode beaker, a backflow preventing the cathodic beaker from overflowing thereby stabilizing the phenomenon for hours."* [Fuchs, 2010, p397]

Charge transport across the bridge also occurs. Although experiments start with de-ionised water, it is clear from tests with pH dyes added after the experiment that charge has been created and transported. Fuchs states *"... there is a charge* *transport mechanism next to the electrochemical one, …"* and demonstrates that operation of the bridge results in a redistribution of charge between the beakers. [Fuchs, 2010, p399]

The obvious possibilities for the charge carriers are protons (H^+), and hydroxide ions (OH^-). [Fuchs, 2010, p282]

> "*The bridge had a reddish colour during all the experiments, indicating that protons were the main charge carriers*." [Fuchs *et al*, 2008, p2]

Less obviously, electrons (e^-) may also be present in significant numbers, despite Castellanos' assumption that they are normally very short-lived in liquids [see Fuchs, 2010, p400]

A recent study by Mucke *et al* (2010) has shown that free electrons may be more numerous in water than previously supposed. They identified *"a hitherto unrecognized extra source of low-energy electrons produced by a non-local auto-ionization process called intermolecular coulombic decay"* which is stimulated by UV light. [Mucke *et al*, 2010, p143]

The movement of any free electrons is unlikely to be significant in terms of the bulk transport of water across the FWB because electrons will not induce significant viscous drag on the neutral heavier water molecules. However, the electrons may play a significant role in the formation of the FWB by initiating the helical particle paths.

Dipole forces on neutral water molecules may also be relevant, as suggested by Fuchs:

> *"… a dipole in the medium experiences a force towards higher field strength. … Since the main flow direction of the water bridge is polarity dependent but there is also always a flow in both directions, both effects [Coulomb electrophoresis & dipolar dielectrophoresis] have to be taken into consideration."* [Fuchs, 2010, p386]

However, the dielectrophoresis effect does depend on the presence of an electric field gradient which will be minimal in a perfectly cylindrical bridge.

Therefore the transport of water in both directions is likely to be indicative of transport of the ions H^+ and OH^- under the influence of the applied electric field, together with viscous drag of neutral molecules.

The simultaneous bi-directional flows towards the cathode and anode appear to be in the core and outer annulus of the FWB respectively. By analogy with a BC, the rotation of the annulus is driven by the ions in that layer being forced to follow the helical magnetic field lines resulting from a balance of electromagnetic forces.

There is some evidence that the outer rotating layer of an established FWB is positively charged, suggestive of this layer containing a predominance of H^+ ions.

> "*Moreover, Lord Armstrong noticed a water flow in both directions, which he associated with a charge transport: "…the facts of the case seem to demonstrate that the negative current flows inside of the positive …""* [Fuchs, 2010, p394]

Further support for this view can be found in the observation that the outer layer rotates clockwise when viewed towards the cathode, consistent with the direction of the magnetic field formed around an axial current in the core.

The clockwise rotation is seen to be in the form of a spiral towards the cathode. [Marin & Lohseb, 2010 p16] It will therefore result in the observed bulk transport in that direction.

The core, therefore, must be supposed to be net negative and contain the OH^- ions. That being the case, there will be a radial electric field between the outer rotating zone and the inner core which will tend to counter the centrifugal forces on the outer layer and contribute to the stability of the bridge.

Fuchs in fact has already noted the stabilising effect of an azimuthal magnetic field around an axial current.

> *"The current causes a magnetic field along the capillary bridge to rise which focuses the electric field resulting in a thick and stable bridge"* [Fuchs *et al*, 2011 p6]

and also the stabilising effect of rotation:

> "*…the high-speed visualization revealed a rotation of the outer bridge layer, which provides additional stability to the bridge."* [Fuchs *et al*, 2008, p3]

although the reasoning behind this last point is not explained.

The radial electric field between the positive annulus and the negative core drives the rotation. The vector cross-product $\mathbf{E_r} \times \mathbf{B_z}$ of the radial electric field $\mathbf{E_r}$ between annulus and core and the axial magnetic field $\mathbf{B_z}$ results in a tangential force and thence a velocity $\mathbf{v}_{\shortparallel}$ which amounts to rotation of the annulus.

Considering the axial stability of the bridge, Fuchs has noted the stable equilibrium between surface tension & ordered dipole bonding caused by a high applied electric field. [Fuchs *et al*, 2007, p6114]

The surface tension must also be balanced in the azimuthal or tangential direction. Two distinct forces will contribute to this balance in the proposed model.

Firstly, the rotation of the outer annulus will cause a 'centrifugal force'. Secondly, rotation of a charged ring generates both an axial magnetic field and a radial magnetic field gradient; the latter tends to expand the ring carrying the current. Both effects will act to mobilise the tangential surface tension.

Therefore the bridge may act as a stressed skin structure under tension in both directions. The bridge's stiffness will be enhanced due to its stressed skin.

This effect may explain the current discrepancy between the very large axial electric field necessary to rearrange Hydrogen-bonded clusters into linear chains and the much smaller field actually necessary to ensure bridge stability.

There is a further effect of the rotating outer layer which may also be important.

As discussed above, the rotating positively-charged outer layer is effectively an azimuthal current. By the Biot-Savart Law, it will create an axial magnetic field in the same direction as the applied electric field.

Therefore the FWB appears to be operating under the same type of field-aligned regime as a Birkeland Current. If this is the case, we can expect this arrangement to be tending towards a force-free state which is inherently stable and a natural outcome of the electromagnetic forces in the bridge.

It must be acknowledged that the precise nature of the balance of electromagnetic forces cannot be exactly the same in the water bridge and the plasma Birkeland Current because the media are different. In particular, counter-flowing positive and negative charged particles in the water bridge cannot follow virtually the same paths in opposite directions because of viscous forces. In a BC, by contrast, the separation of protons and electrons can be much smaller.

This probably explains the development of an annulus and core structure in water in response to forces which generate the helical pattern in plasma.

Nevertheless, the similarities are so striking that it appears as though similar forces are being generated. The characteristics of the final form suggest that the bridge, consisting of a partially-ionised fluid, is achieving a similar balance of electromagnetic forces as an ionised plasma does in similar circumstances.

Furthermore, the bridge may also be an efficient charge transport mechanism due to the enhancement of the current and associated viscous drag by the Schönherr Whirl Stability effect in which a significant increase in current is achieved when a conductor is rotated about its axis.[see Peratt, 1992]

The above analysis offers some additional insights as to the response of the 'final form' of the FWB to an applied electric field. In particular:

- The charge-separated *Annulus and Core arrangement* probably develops in tandem with the growth of a radial electric field and the start of rotation of the Annulus.
- Rotation of the positively-charged Annulus combined with axial current flow mirrors the particle paths in a Birkeland Current, which allows development of *an axial magnetic field* and radial magnetic field gradient.
- The field-aligned nature of the final form results in an *efficient flow mechanism*; the charge separation of the heavy ions into Annulus and Core allows simultaneous *bi-directional flow*, augmented by viscous drag of neutral water molecules.
- The combination of the radial magnetic field gradient together with centrifugal forces mobilises the water bridge surface tension in the tangential direction. The axial electric field mobilises the axial surface tension. In combination, the result is *a stressed skin structure of high stability*.

Application of the Principles of a Birkeland Current to Biological Transport

It has been demonstrated above that the principles of plasma behaviour in Birkeland Currents also apply to the phenomenon of the Floating Water Bridge where they cause rotation of the outer layer in a charge-separated 'Annulus and Core' structure and underpin features of the bridge behaviour including:

1. Enhanced stability of a water bridge in air
2. Bi-directional charge and mass transport
3. Efficient flow parallel to a self-created axial magnetic field.

We explore below whether these principles may also play a part in biological situations.

We start by describing research by Pollack into the behaviour of water in more general situations.

Pollack [2001, p62 & ff] has demonstrated that water in contact with hydrophilic surfaces forms a structured layer of the order of $10^2 – 10^3$ µm thick adjacent to the surface; the structured layer is termed an Exclusion Zone, or EZ water. The structure arises from dipole ordering perpendicular to the surface and results in changed physical properties including increased viscosity. The EZ layer is also negatively charged even when the surface itself is electrically neutral.

Pollack also suggests that the negative charge resides on the electropositive Oxygen atoms in the water molecule.

However, Mucke *et al [2010]* have recently demonstrated that water is capable of generating significant numbers of free electrons by auto-ionisation under the influence of incident radiation. It seems possible that at least some of this electron population may remain as free electrons in the EZ layer and contribute to the observed negative charge of the zone.

Recent research by Yu, Carlson & Pollack [2011] involved water in contact with 2-3 mm diameter Nafion tubes and tunnels formed in PAA gels. As expected, a negatively-charged EZ annulus develops inside the tube or tunnel, leaving a central core area of unstructured water.

Unexpectedly, an axial flow in the core develops automatically without any external pumping mechanism. The core was found to contain positive hydronium ions H_3O^+ Yu *et al* ascribe this flow to radiation-induced ionisation inside the tube itself which causes an ion gradient to develop along the tube. Unspecified asymmetries determine that the flow is usually unidirectional. Once established, the flow is maintained by the steep ion gradient between the accumulated ions at the outflow end of the tube and the water in the outflow reservoir.

Johnson [2011] has offered an alternative explanation of the unidirectional self-generated flow which takes account of the observed but unexplained tapering thickness of the EZ layer inside the tube. The thickness of the EZ layer decreases towards the outlet end; correspondingly, the diameter of the positive core increases in the direction of flow.

Johnson hypothesised that the negative charge volume density in the EZ layer is constant and that each cross-section of the tube automatically tends towards electrical near-neutrality. The decreasing thickness of the EZ layer and the increasing area of the core in the direction of flow will both lead to decreasing positive charge density in the core with increasing axial distance in the flow direction.

Therefore the ion gradient is *created* by the presence of the tapered EZ; it is automatically in the direction of flow because flow follows the gradient; and positive ions will be actively drawn into the inlet end to replace ions 'lost' to the entry cross-section by flow along the tube.

At the outlet end, flow is forced from the tube by the accumulation of ions in the flow which, unless rejected from the tube, would imbalance the charge at the outlet cross-section. This explains why the flow can be maintained against increasing ion concentrations in the outlet reservoir.

However, other effects may also play a part as well.

The positive core together with the negative EZ annulus appears to be similar to the arrangement of a FWB except with the charges of the core and annulus reversed.

Is this merely coincidental or could similar principles apply to both cases? Can the FWB and plasma principles offer any insights into the self-generated flow observed in the tubes and tunnels?

Obviously, there are some fundamental differences. Firstly, the tube or tunnel is a structure which is absent in the FWB. Secondly, the EZ layer is prevented from rotating by its higher viscosity and contact with the tube. And thirdly there is no external electric field.

But suppose that there are free electrons in the negatively-charged EZ layer, as suggested above. They would be free to rotate within the EZ in the same manner as electrons in a metal conductor. They can then assume the role of the rotating parts of the Birkeland Current model.

There is then a direct analogy with a plasma Birkeland Current. As already discussed, this should lead to enhanced efficiency of flow in the axial direction.

It appears that plasma behaviour in Birkeland Currents may well be mirrored in hydrophilic tubes.

The effects of the diamagnetic nature of water in the variable axial magnetic field may also be significant. Repulsion of the diamagnetic water molecules from regions of stronger field to regions of weaker field generated by the tapering EZ layer will enhance the flow mechanism already discussed.

Roots

Turning to biological flows, we find evidence of enhanced flow efficiency in various situations. The first one we will look at is plant root growth.

A growing root tip is a cul-de-sac which needs to get its nutrients from the main root system. That's a problem if the root tries to grow fast but has to rely on slow diffusion of nutrients down the cul-de-sac to deliver materials for making new cells.

But plants seem to have found a solution: Steudle observed:

> *"During root development, the axial resistance in onion was reduced by **three orders of magnitude**.* [emphasis added] *The differences between measured and calculated values of axial hydraulic resistances are known from the literature. They may be referred to the fact that the assumption of ideal cylindrical capillaries does not hold or to difficulties in identifying all vessels in stained cross sections.* [Steudle, 1994, p83]

Note the suggested explanations for the discrepancy between theory and observation. Is it possible that other forces are involved in addition to the relatively slow and inefficient ion diffusion mechanism?

When we look at what's already known about flow in growing plant roots, some familiar features appear, viz:

- Annulus and Core bi-directional flows of sap in the root
- The sap includes inorganic ions, that is it contains charged particles and is therefore a partially-ionized liquid.
- The flow of charged sap forms an electric current which will cause an circular magnetic field.
- And we know from Pollack's work that an EZ layer will form inside the cylindrical root cortex, outside the flowing annulus

So parts of the now-familiar plasma pattern are already in place and more can be added if the EZ layer is taken into account.

Firstly, the EZ layer is known to contain electrons which are what make it negatively charged. They are normally assumed to be bound to the water molecules. [Pollack, 2001]

However, as discussed above, recent research by Melanie Mucke *et al* [2010] has shown that water unexpectedly contains free electrons, like electrons in a metal conductor.

We hypothesise that the following situation may exist:

At least some of the electrons in the EZ layer are in the 'free' state. That means they are able to spiral round the EZ layer and play the part of the rotating layer in a Birkeland Current-style helical pattern.

Spiralling electrons will generate an axial component to the magnetic field. Then a Birkeland Current helical arrangement can emerge.

That would imply an efficient bi-directional flow in the annulus and core, enhanced by the spiralling electrons in the EZ layer.

One more factor needs to be included. A charge-separated annulus and core is necessary for the model to work, but the same sap has to flow down the annulus and back up the core after turning round at the tip.

That implies that the net charge of the sap changes at the root tip. This could be achieved if charged material is deposited at the growth site in the meristem region just behind the root tip.

If that change in the sap charge is from net positive to net negative, then the annulus and core will be charge-separated as the model requires.

It appears that growing onion roots may use plasma principles and the EZ layer, which together can explain the Annulus and Core arrangement, the reduction in axial flow resistance, and the reversal of the flow at the root tip.

Blood

Flow in blood vessels is also known to demonstrate a 'core and annulus' arrangement with the red blood cells being constrained to the core.

The classic 1967 paper by Whitmore states:

> *"The theory is based on the red cells forming a shearing core when flowing in large vessels and an axial train when passing down vessels whose diameter is comparable to the dimension of the cells.*
>
> *... The theory is used to explain various observed peculiarities of flow in the microcirculation."* [Whitmore, 1967, p767]

But again discrepancies are observed and corrections are required to the model:

> *"Although this model may give satisfactory representation of flow in large vessels, observation shows that in a living capillary the red cells, which constitute the bulk of the dispersed phase, tend to follow each other in a single axial file, with their discoidal surfaces predominantly (but not universally) perpendicular to the vessel axis. As the flow rate rises, deformation is observed, the cells often becoming thimble-shaped and their effective diameter decreasing. A better model in this case consists of an axial train of cells moving with their discoidal surfaces normal to the direction of flow and interspersed with plasma, surrounded by a sleeve of plasma in which the shearing takes place. The train of cells and interspersed plasma travel as a single cylindrical unit possessing infinite viscosity,…"* [Whitmore, 1967, p767]

The infinite viscosity of the inner cylindrical core is, of course, atypical fluid behaviour and more suggestive of a flow driven by forces on individual components of the flow rather than a hydraulic pressure resisted by sidewall friction.

The Whitmore model is still current: for example, Sharan & Popel state in 2001:

> *"A two-phase model for the flow of blood in narrow tubes is described. The model consists of a central core of suspended erythrocytes and a cell-free layer surrounding the core."* [Sharan & Popel, 2001, p 415]

Whitmore's 'axial train' of cells is now known as a rouleaux.

Goldsmith and Spain describe the formation:

> *"... as the flow rate decreased, erythrocytes [red blood cells] formed rouleaux which migrated inward creating a core and displacing leukocytes to the periphery."* [Goldsmith & Spain, 1984 p204]

The formation of the rouleaux appears to be dependent on the presence of macromolecules. Proteins are effective in this regard, but the exact mechanism is unexplained.

We suggest that the formation of rouleaux may be an application of the 'like likes like' principle operating between the negatively-charged RBCs and mediated by positive ions in the blood plasma. The presence of negatively-charged macromolecules may serve as intermediaries which allow the RBCs to maintain a separation dictated by Coulomb repulsion.

Strangely, the formation of rouleaux is associated with a *reduction* in the resistance to flow in capillaries.

As Cokelet & Goldsmith [1991] stated:

> *"The aggregation of red blood cells in blood flowing through small tubes ... leads to the two-phase flow of an inner core of rouleaux surrounded by a cell-depleted peripheral layer. The formation of this layer is known to be accompanied by a decrease in hydrodynamic resistance to flow."*

It appears that plasma principles can help explain this behaviour as described below.

There is an annulus and core arrangement, even though the annulus doesn't flow because it acts as the shear layer for the core.

Kung-Ming Jan stated back in 1973, *'it has long been recognised that .. Red Blood Cells are negatively charged'*. Therefore the core carries charge in the form of the RBCs, together with proteins and ions in solution. Blood is therefore also a partially-ionised liquid, as are water in the FWB and sap in onion roots.

Assuming a net charge imbalance as indicated by blood Standard Reference Intervals [Longmore *et al,*2001] , this means that the flow forms a current. The current generates an azimuthal component of the magnetic field in the usual way. Again, this may result in spiralling free electrons in an EZ layer lining the vessel walls.

But Red Blood Cells also have magnetic properties which Spees has investigated and modelled.[Spees *et al*, 2001]

Briefly, RBCs are diamagnetic. In the presence of a magnetic field, a cell will form a magnetic dipole to repel the external magnetic field, which means the cell will itself be *repelled* by the field.

In Spees' model, the degree of diamagnetism is a function of the level of oxygenation of the cell. Fully oxygenated cells are more diamagnetic than both partially and deoxygenated cells and would therefore experience greater repulsive forces in a given field.

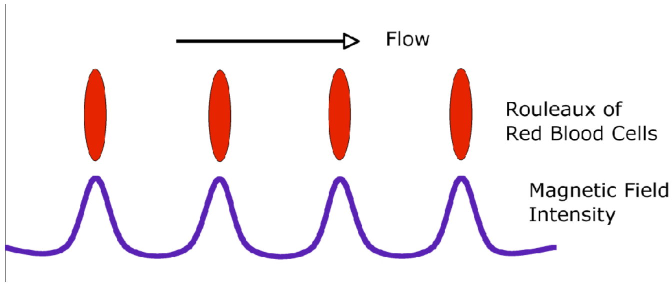

Figure 2. Diagrammatic representation of Magnetic Field created by RBCs

In a rouleaux arrangement, the cells proceed one by one in an axial train down the capillary. Each charged cell will generate its own azimuthal magnetic field component because it acts as an element of axial current.

This will increase the magnetic field in the vessel cross-section in which the cell is situated. The magnetic field intensity will effectively have a spike or wave peak centred on the cell location.

But the cell is diamagnetic and is repelled by a magnetic field. That means it will be forced away from the wave peak that it's creating. It will move down the magnetic field gradient, like surfing the wave.

The heart is still driving the flow, of course, so the preferred direction for the cell to go is forwards.

In large blood vessels, the individual peaks of magnetic field intensity from all the individual cells tend to average out so the effect is not significant. The hydraulic pressure is enough to drive the flow because the diameter of the blood vessel is large; the flow may also be assisted by field-aligned effects utilising spiralling electrons in an EZ layer, as we saw in the case of onion roots.

However, in capillaries the 'one by one' progression of the cells in a rouleaux formation allows a magnetic intensity peak to form for each cell and not be averaged out.

In other words, I suggest that diamagnetic repulsion of each cell will assist the heart's hydraulic pressure to move the Red Blood Cells through narrow capillaries when they are aligned in rouleaux.

This will appear as though the hydrodynamic resistance to flow has been reduced, as the experiments show.

Once again, electromagnetic principles of plasma behaviour seem to offer an explanation of anomalous natural behaviour in a partially-ionized liquid.

Electromagnetic forces can help explain the formation of rouleaux by the 'like likes like' principle, the mechanism whereby the rouleaux arrangement leads to additional driving forces, and therefore the anomalous reduced resistance to flow in capillaries.

Conclusions

The principles of plasma behaviour in Birkeland Currents have been shown to apply to the dynamics of the Floating Water Bridge and to offer explanations of aspects of the behaviour of the bridge which are unexplained by EHD and QFT analyses.

We suggested that the ionized water bridge appears to behave according to plasma principles, driven by complex electromagnetic forces.

The core and annulus flow pattern is common to both the FWB and to hydrophilic tubes which create structured water EZ layers on their inner surfaces. The same behavioural patterns may offer an explanation of the apparent efficiency of the self-generating flow mechanism in such tubes. The role of the EZ layer may be to carry spiralling free electrons which Mucke *et al* have demonstrated to be present in water.

Similar flow patterns and anomalously high flow efficiency are also found in plant roots; this suggests that similar mechanisms may also be involved, again involving free electrons in an EZ layer. Ionised sap appears to obey plasma principles too.

The same principles may also apply to larger mammalian blood vessels, although in this case the annulus does not rotate. The situation may therefore be nearer to the hydrophilic tube case than to the plant root case.

The anomalous alignment of diamagnetic Red Blood Cells in axially-aligned rouleaux within capillary blood vessels can also be explained by the electromagnetic principle of 'like likes like' modulated by the positive ions present in blood plasma.

The role of the rouleaux arrangement appears to be to allow generation of peaks of azimuthal magnetic field intensity which drive the diamagnetic RBCs forward, thereby assisting the heart's hydraulic pressure in the narrow vessels, and explaining the anomalous reduction in apparent hydraulic flow resistance.

Further research into the electromagnetic behaviour of the various phenomena is necessary to confirm or refute the hypotheses put forward in this paper. If confirmed, the suggested model could represent a significant contribution towards resolving a number of anomalies in observed flows in partially-ionized liquids.

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