

中文摘要

本研究中，吾人利用數值模擬及碳纖維展開實驗成功地發展了一部高效能碳纖維氣體展開床，並將碳纖維紗束以 1:1 的氣體展開器在各種不同條件下進行展開實驗，且於實驗中利用攝影技術記錄纖維展開過程，基於本研究歸納所得結果如下：

1. 本文成功地應用遠場邊界條件於纖維氣體展開器之三維網格，探討內流場之流動形態；並利用有限體積法結合 $k-\varepsilon$ 紊流模式求解三維不可壓縮之雷諾平均納維爾-斯托克氏 (Reynolds-averaged Navier-Stokes RANS) 方程式；且將纖維氣體展開器於不同的工作壓力條件下，以速度及壓力分佈分析內流場的流動形態並進行探討，最後將計算數值與實驗量測結果比較，結果發現定性上有相同的趨勢，且在定量上得到相當符合的結果，證明此三維流場的分析可應用於纖維氣體展開器之設計。
2. 本研究成功地設計一高效能碳纖維展開系統，並定義了新的變數-展開均勻度，用於說明碳纖維紗束在氣體展開過程中分散均勻的程度，藉此變數展開的碳纖維可做一定量的比較；並可容易的獲得纖維展開的最佳工作條件。此外，由計算的模擬及展開實驗，我們可瞭解碳纖維分散的機制及纖維與氣流交互作用的行為。
3. 為了證明藉由氣體展開製程可克服碳纖維紗束不均勻鍍層的結果，將碳纖維紗束分為展開與未展開兩組，比較無電鍍鍍後的結果。結果證明展開的碳纖維紗束可被覆均勻的金屬鍍；且鍍層厚度可低於 $0.2 \mu\text{m}$ 。這是首次金屬鍍可均勻度著於紗束內所有纖維表面；且藉氣體展開系統可克服製程表面處理不均的問題。

Abstract

In this study, a high efficient carbon fiber tow pneumatic spreading system was successfully developed by means of numerical simulation and carbon fiber spreading experiment. Carbon fiber tow was spread on 1:1-scale model of the pneumatic spreader at various conditions, and photography techniques were simultaneously used to record the procedures of fibers spread. Based on the investigation, some results can be summarized as follows:

1. The three-dimensional numerical analysis was carried out on incompressible fluid flows by using finite volume method combined with the k- turbulence model which solves Reynolds-averaged Navier-Stokes equations. Comparisons of numerical results with measured velocity and pressure distributions were made, and a good agreement was found in both qualitative and quantitative analysis. The performance was better than prior studies in one-dimensional orifice formulation. Agreement among those results validated the assumptions inherent to the computational calculation and gave confidence to more complex geometries as well as flow fields.
2. The work successfully designs a high efficient carbon fiber pneumatic spreading system. A new variable, spreading evenness, was defined to specify the dispersing extent of fibers in a carbon fiber tow during the fiber pneumatic spreading process. By the spreading evenness, a quantitative comparison of a spread carbon fiber tow can be made and the optimum condition can be easily obtained at fiber spreading experiments. Also, by the computational modeling and the spreading experiment, both the dispersing mechanism of carbon fibers and the interaction between the fibers and the airflow were understood.
3. To identify the non-uniform coating in a carbon fiber tow can be overcome by the

pneumatic spreading process; two groups of spread and unspread carbon fiber tow coated with nickel by electroless plating were compared. The results showed that a uniform Ni coating could be obtained on each fiber in the spread carbon fiber tow, and the thickness of the Ni film could be coated on carbon fiber tow less than 0.2 μm , and it's the first time the Ni thin film can uniformly be coated on the fiber surface in the overall fibers.



誌 謝

博士班求學的過程中，承蒙恩師朝春光教授引領導，得使愚生順利完成學業，謹致上最深謝意與敬意。同時也感謝口試召集委員交大機械系主任傅武雄教授在數值模擬及流場實驗所提供寶貴的意見；感謝中央大學機械系李勝隆教授在機構應用上所提供的珍貴想法；感謝聯合大學材料系主任林惠娟教授及大同大學材料系楊智富教授詳閱論文，並在炎炎夏暑中驅車前來指導，謝謝您們所給予的指導，使本論文更臻完善。

其實這篇論文的完成要感謝陳景松先生，他是我的好同學也是我的好哥兒們，感謝他給我靈感及碳纖維材料的資助，使我能夠充分發揮，進行實驗，雖然很久沒有聯絡而且也很難聯絡，但我始終沒有忘記他給我的鼓勵，要我畢業後送一本論文給他，我想這本論文是我對他最大的謝意與敬意。

96 年盛暑考進了交大材料所，一切事物是如此地新鮮，尤其是研一舍頂樓 R422 豪華冬冷夏熱房，一進門汗如雨下，即使是全國大專盃柔道銀牌得主吳彥霖同學也難以停留片刻。不過，如果不是彥霖及俊銘我真的不知道如何收拾前位畢業學長留下的殘局。他們很積極也很勤快，凡事喜歡自己 DIY，記得和彥霖一起去買角鋼、木材製作了書架、材料架及工具架，我記得為了做流場實驗，必須製作煙霧分散器，多虧了彥霖使我成功地完成了放煙實驗。在 97 年以前工一館的所有材料研究室包含機械工廠沒有自己的網路，必須經由工二館才能連上計中上 Internet，所以每次要 RUN 電腦都得跑到國家高速電腦中心上機，雖然有了 data，但是龐大的數據仍無法傳回實驗室處理，在這一刻除了俊銘我幸運地遇到了 4 位重要的人，海大造船系林明慶及陳建偉同學及工研院化工所的井長慧小姐及目前服務於中科院原子能研究所的謝仁雄先生，感謝您們提供服務單位的超級

電腦及工作站，使我能順利的處理大量的數據，特別是謝仁雄先生利用工作時間教導我 ICEM-CFD 及 CFX4.1 的使用介面讓我能夠很快的上手進行數值模擬的工作；此外因為俊銘的幫忙使工一館的整個網路能獨立運作。

96 年與我一同入學的景恆學長、汶真、駿發、嘉文、志展、來興、大敏在一同學習的日子中，使我能更認真更深入的思考，不斷地回顧所學萃煉自己使我更精進。記得常跟景恆學長熬通宵寫第一版的擴散學及相變化作業，常跟汶真在實驗室討論固熱及 ECAE 的加工，和駿發一同冒險犯難地擠壓鑄造製做複合超強磁性材料；因為志展、來興與大敏常過來討論 TEM 及試片製做使得 MMC 實驗室更為熱鬧吸引許多同學依起來討論學業，因此常被喻為交大的 7-11，24 小時營業。在此時因為定侃、國強、勝文及肇男的加入使得 MMC 實驗室邁向全盛時期，也因為他們使 MMC 實驗室成就了一段光榮歲月。

特別地我要謝謝志展與來興；即使志展碩士班已畢業，他時常下班後就回來實驗室陪我做實驗討論工作上一些技術問題，使我能提早了解業界發展的狀況及工業應用上的問題。志展是一位工作熱忱非常高的好兄弟，他很清楚知道自己要什麼，要往哪裡發展，明確地規劃自己的未來，一步一步踏實的去實現它，因為他有這個優點同時也暴露他的小缺點，玉真說他不夠浪漫，但是只有雙魚座的我了解他的浪漫，記得有一次志展惹惱了玉真，還是出動了我才解除這次的千禧危機。現在看到他們夫妻倆仍彼此恩愛的生活在一起，真為他們感到高興。

來興也是一樣常下班後就來交大慢跑，跑完校園後就到實驗室看看我，常鼓勵我替我加油。也會介紹一些工作訊息給我，讓我了解未來發展的方向。來興他是一位對工作很有規劃而且有衝勁的人對未來充滿希望與熱忱，雖然他目前有一些不順，但是我想他會很快地理出一個方向，繼續勇往直前。他也很會看人，常告訴我學校外現實的一面，我想因為他的這項優點使他能找著雅萍這樣一位溫柔

婉約的好女孩，真希望能早一點收到他們的好消息。

汶真是一位很聰明也很有才華的一位學弟，是實驗上他總是能夠很清楚地規劃自己的工作，很多困難的事情到他手中都變的簡單了，汶真的口才不錯，很喜歡說笑話，當我覺得心情不好或沮喪時，跟他聊聊天心情總是會開朗很多，因為他實驗室常有一種輕鬆愉快的氣氛，他讓我印象最深刻的事，他在碩士班等通道擠形(ECAE)的實驗中從模具設計到擠形階段能完整的實現，顯現他的確是一位能力很強的人。希望日後他在工作上有傑出的表現更上層樓。

定侃是一位亦師亦友的學弟，雖然他晚我一年進 MMC 實驗室，但是在研究學業、實驗工作上以及做人做事上是我學習的榜樣，還記得他剛來的第一年他得新竹、雲林、台中三地往返顧及學業、事業及家庭表現出超人的能耐，雖然他如此忙碌但是他的家事一點也沒有耽誤，入學二年，年年得子，這是讓最敬佩之處，只是很遺憾他一直不告訴我他的撇步，希望他看完這個致謝後能將這不傳的秘方告訴我。



在三十歲以後影響我最多的人應該是國強學弟，記得他剛進實驗室時由於彼此的不了解使學長們以為他是一位心高氣傲的人，最明顯的事為每次進實驗室就一屁股的坐在椅子上玩自己的電動，像小孩子一般，其實他是一個外冷內熱的人，熟識之後就會發現他是一位很熱心且熱忱之人。理論上來說，他是一位打破 MMC 許多傳統的傳奇”性”人物，他是第一位將即時戰略遊戲及成人性事物引進實驗室的人，增廣了我的見聞；也是打破工一館各研究室間藩籬的人，凝聚了工一館所有心裡仍有一碗綠豆湯的人。國強的另外一面是在研究及工作上嚴肅且嚴謹的人，他很有研究的天份及工作的熱忱；在我博士班的歲月中，常伴我到凌晨三時熄燈的人，他的才能讓我用孔子的話來描述他「於學問，吾不及強也，吾能舉一反三，強嘗能舉一反十」。國強不僅是我的學弟也像是我的弟弟，常常有人以

為我們是兄弟，因為他總是為我著想，常鼓勵我，在我心情沮喪及研究遇到阻礙時總是在一旁勉勵我，在他的研究工作中，只要我有一些幫忙他不會忘記把我的名字掛在他的研究著作中，從很多小地方可以看的出他是一個很細膩很為人著想且有情有義的人，在博士班期間有些事情讓脆弱的我曾想放棄，因有他的鼓勵及勸說讓我重拾信心繼續走下去，真的非常感謝他的支持。其實看到國強就像看到自己的另外一面，從他進碩士班，畢業，服國防役，退伍，正式成為國家實驗室的副研究員，看到他成長就像看到自己的成長一樣，現在讓我同他父母操心他的事情只有一件，祝福他跟瓊枝有幸福美滿的未來。

勝文是一位認真負責的學弟也是一位榮譽心很高的人，遇到困難他會努力去想辦法解決，不輕易麻煩別人，是一位韌性強且抗壓性高的學弟，他寧願做各種嘗試也不會取巧閃躲，同時他也是一位得人點滴泉湧相報的人，所以在博士班期間他總是盡力幫我，能夠讓我在國家高速電腦中心擁有足夠的帳號使用資源；在他畢業後也常提供我工作資訊，感謝他始終沒有忘記我這位學長。

在進交大前就承蒙欣瑩的幫忙，她是一位熱心且善良的學妹，只要儀器使用上有任何問題他都會想辦法幫忙處理，此外她也會招待實驗室的學弟妹到她家享受一頓豐盛的佳餚，每年大家都會很期待去她家，她們一家人從老公到小朋友都非常熱情，我也很敬佩她對孩子的教養，因為她的孩子是如此地循規蹈矩，希望我以後也能做的像她一樣。

在此我也要感謝老姬，每次在壓鑄時我的腎上腺素就會飆高，那種刺激是沒有別的事物可以取代，因為有這種共同的革命情感，所以總是讓他對我感到特別敬佩，因為總是我站在最前線替他擋子彈。我要謝謝他常問候我學校的狀況及介紹我好的工作。

最後我要謝謝李秉章學長在投稿上的幫助；謝謝常孝宗學長幫我做影像的分

析及處理；謝謝薄慧雲學長在學業上的幫助並提供許多的資源；謝謝俊沐哥再學業上所提供的意見；謝謝肇男學弟在研究上所提供的協助；謝謝治平學弟幫我製作暗房使我能夠順利拍攝流場；謝謝昇翰學弟幫我架設電腦及網路使我能夠順利處理資料連上高速電腦中心，此外也謝謝他在碳纖維展開實驗上的協助，雖然他畢業了，但仍時常打電話問候我，希望他能夠順利在 UCLA 獲得博士學位；謝謝仁豪學弟在實驗室的幫助也謝謝他及女友在我行動不便時的協助；謝謝燦璋學弟常陪我熬通宵做實驗也因為如此我們挽救工一館不為大火所吞噬；謝謝德人學妹在我投稿時幫我打字；謝謝建仲學弟幫忙處理實驗室的事物以及在電化學、AAO 上所提供的寶貴意見；謝謝有函學妹在論文及口試時的協助；謝謝芳慰學弟教我健身養身陪我做運動；謝謝金國學弟、兆鼎學弟、祺淵學弟、蓉萱學妹、建財學弟、家茵學妹、晏辰學弟、清陽學弟、文翔學弟、柏均學弟在口試的階段給予協助及幫忙連絡；特別謝謝阿財學弟幫我辦理離校的流程；也謝謝麗娟、慧馨、瑞玲在口試上的協助與幫忙。



這部流體展開床的完成，要感謝高雄的陳敏昆老闆在製做這部機器時他提供許多寶貴的經驗一再地幫我修改並提供場地讓我測試，使我日後能順利的工作，由衷的感謝他並祝福他鴻圖大展。

在此謝謝我的家人，謝謝我的父母在博士班期間給我的支持能夠讓我全心全意的攻讀；謝謝弟弟仁帥幫忙分擔家計；謝謝大妹仁娃提供我許多生活上的協助；謝謝二妹仁姪在國外唸書時沒忘記幫我帶紀念品回來；謝謝三妹仁教對我健康上的關心；謝謝岳父、岳母關心我的學業及健康，幫我向神明祈禱；謝謝大舅子順添、小舅子順晏對我的關心，有好料的總不會忘記我；謝謝我的太太真真，其實說謝謝是太單薄而且不夠的，論文能夠完成多虧她連哄代騙，迫我去寫論文，最後的論文稿件也多虧她幫我打字校稿編排，我只能以生命相許，希望她能

夠接受。

攻讀博士班的初衷只是為了完成自己一個想法，想去證明自己的理論是正確，博士學位對我來說只是一張紙而已，從沒想過用一張紙去證明自己的能力，但是今天能夠完成，不是我自己一個人能夠辦到的，對我來說這一本論文它不是一個研究的成果，而是維繫 11 年來所有共同經歷這一段人的心。謝謝天，謝謝地，謝謝所有的一切讓我與真真能夠在這裡表達心裡的感謝！



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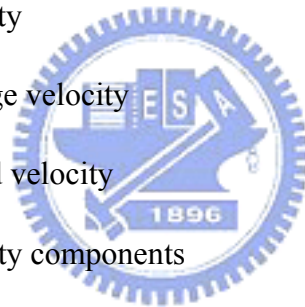
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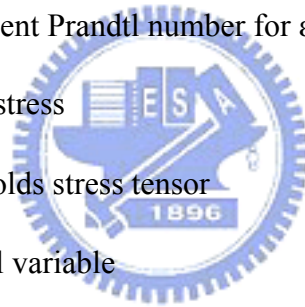
Nomenclature

A	cross-sectional area
c_1, c_2 and c_3	empirical coefficient
E	empirical coefficient
k	turbulent kinetic energy
p	pressure
t	time
$\overline{u_i u_j}$	Reynolds stress tensor
u_i, u_j	fluctuation parts of the velocity
u_j	velocity
\bar{u}	average velocity
u^+	scaled velocity
U, V, W	velocity components
V_F	fiber transported velocity
x, y, z	Cartesian coordinates
y^+	dimensionless distance



Greek Characters

ε	turbulent dissipation rate
μ_τ	turbulent viscosity
k	Von Karman constant
ξ, ζ, η	curvilinear coordinate
ν	molecular kinematic viscosity
ν_T	eddy viscosity
ρ	density
σ_k	turbulent Prandtl number for k
σ_ε	turbulent Prandtl number for ε
τ	shear stress
$\tilde{\tau}_{ij}$	Reynolds stress tensor
φ	general variable



Mathematical operators

del operation

∂

partial derivative

