UNIVERSITI PUTRA MALAYSIA

NUMERICAL INVESTIGATION OF LAMINAR FLOW AND THERMAL CHARACTERISTICS OF TANGENTIAL COOLING AIR JET IN A SUDDEN EXPANSION CHANNEL

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By

ASGHAR PISHGAHI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

May 2012

Dedicated to:
LATE **ZAHRA (MAHNAZ) CHITSAZYAN**
LOVELY WIFE
PhD Candidate @UPM
1963-2011

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Doctor of Philosophy

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Chairman: Abdul Aziz bin Jaafar, PhD

Faculty: Engineering

This thesis describes a study of tangential jet flow in a sudden expansion channel referred to as a Backward Facing Step (BFS). A two dimensional laminar air flow was investigated numerically by introducing a cooling air flow injected tangentially through a slot on the step. The goal of the study is to gain an insight on the relationships between the axial momentum of the cooling air and characteristics of the flow and heat transfer by performing systematic assessment on the geometrical, kinematic and dynamic properties of the fluid. The Top-wall had a constant temperature (T_w) of 35˚C. All other walls were adiabatic. The static temperatures of the mainstream T_∞ and tangential jet flows (T_c) were assumed constant at 50˚C and 20˚C respectively. The BFS had an expansion ratio (ER) of 2. In the numerical experiments, the main channel Reynolds number (Re) was varied from 100 to 800 for a range of velocity ratios ($\Lambda=Vj/V\infty$) between 0 (backward facing step flow) and 1.0 (tangential jet flow in BFS), and of ratios of slot to step heights (ℓ=slot

height/step height) between 0.1 and 0.5. The simulations were performed for air with a constant Prandtl number (Pr) of 0.71.

The governing equations of motion and energy for two-dimensional laminar flow were discretized by a finite volume method. The resultant algebraic equations incorporated in the modified TEACH-T code were solved by treating the combined convective and diffusion terms using the hybrid differencing scheme. The elliptic solver was modified to reduce the computational time by integrating the prediction from multiple solution sub-domains.

The BFS flow is characterized by the primary and secondary recirculating flows on the Top-wall and Low-wall respectively, and the occurrence of small recirculating flow at the corner regions. The tangential jet flow is introduced into the main channel. The thermal analysis was presented to investigate the influence of convection heat transfer through the Top-wall. Two simulated conditions were studied; BFS flow with and without tangential jet flow. The predictions were compared against previous studies.

For constant values of Re, the strength of primary and secondary recirculation were reduced with increasing ℓ. Increasing the axial momentum of the jet produced larger friction coefficient but reduced rapidly the air temperature in the corner region. The occurrence of film flow in the main channel by the tangential jet flow eventually reduces the amount of convective heat transfer.

At constant ℓ, the Moffat eddy and the secondary recirculation flow were removed, and the strength of the primary recirculating flow was attenuated for $\Lambda>0$. The

tangential jet flow affects the rate of heat transfer and reduces the maximum Nu. Increasing Λ significantly affects the film cooling effectiveness (η) particularly in the corner region compared to ℓ and Re. The uncertainty analysis and statistical analysis of the numerical results shows that the predictions were in acceptable and reliable range.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi sebahagian keperluan untuk ijazah Doktor Falsafah

PENYIASATAN BERANGKA CIRI ALIRAN LAMINA DAN TERMA JET PENDINGINAN TANGEN UDARA DALAM ALUR DENGAN PENGEMBANGAN MENDADAK

Oleh

ASGHAR PISHGAHI

Mei 2012

Pengerusi: Abdul Aziz Bin Jaafar, PhD

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Tesis ini menerangkan kajian aliran jet tangen dalam saluran pengembangan secara tiba-tiba disebut sebagai Tangga Mengbadap ke Belakang (BFS). Aliran udara dua lamina dimensi berangka disiasat dengan memperkenalkan aliran udara pendingin disuntik tangen melalui slot pada langkah. Matlamat kajian adalah untuk mendapatkan pandangan mengenai hubungan antara momentum paksi udara penyejukan dan ciri-ciri aliran dan pemindahan haba dengan menjalankan penilaian yang sistematik ke atas sifat-sifat geometri, kinematik dan dinamik bendalir. Dinding bahagian bawah mempunyai suhu malar Tw 35˚C. Semua dinding lain adiabatik. Suhu statik arus perdana (T_∞) dan aliran jet tangen (T_c) dianggap malar pada 50˚C dan 20˚C masing-masing. BFS mempunyai nisbah pengembangan (ER) 2. Dalam ujikaji berangka, nombor Reynolds saluran utama, (Re) telah diubah 100-800 bagi pilihan nisbah halaju ($\Lambda = vj / V\infty$) antara 0 (mundur menghadapi aliran langkah) dan 1.0 (aliran jet tangen di BFS), dan nisbah slot langkah heights (ℓ) antara 0.1 dan 0.5.

Simulasi telah dijalankan untuk udara dengan satu nombor malar Prandtl (Pr) dari 0.71.

Persamaan yang mengawal gerakan dan tenaga untuk dua aliran lamina dimensi discretised oleh kaedah isipadu terhingga. Persamaan algebra paduan yang diperbadankan di kod TEACH-T telah diselesaikan dengan merawat digabungkan perolakan dan terma resapan yang menggunakan skim differencing hibrid. Penyelesai elips telah diubahsuai untuk mengurangkan ditetapkan masa pengiraan dengan mengintegrasikan ramalan dari penyelesaian beberapa sub-domain.

Aliran BFS dicirikan oleh aliran perhitungan kembali rendah dan menengah atas plat bawah papak dan atas masing-masing, dan berlakunya aliran kecil perhitungan kembali di rantau sudut apabila aliran jet tangen diperkenalkan ke dalam saluran utama. Analisis terma yang dibentangkan untuk menyiasat pengaruh pemindahan haba konduksi melalui papak bawah. Empat syarat-syarat yang simulasi yang dikaji; aliran BFS dengan dan tanpa pemindahan haba konduksi melalui papak, jet aliran tangen dalam BFS dengan dan tanpa pemindahan haba konduksi melalui papak. Ramalan telah dibandingkan dengan, misalnya, kajian yang lepas.

Untuk nilai yang berterusan, kekuatan edaran semula yang rendah dan menengah telah dikurangkan dengan peningkatan. Kesan meningkatkan momentum paksi jet juga menghasilkan pekali geseran yang lebih besar tetapi dikurangkan dengan cepat suhu udara di rantau sudut. Berlakunya aliran perhitungan kembali antara utama dan aliran jet tangen akhirnya mengurangkan jumlah pemindahan haba perolakan.

Pada ℓ malar, pusar Moffat dan aliran edaran semula menengah telah dimansuhkan, dan kekuatan aliran utama perhitungan kembali dilemahkan untuk $\Lambda > 0$. Aliran jet tangen mempengaruhi kadar pemindahan haba dan mengurangkan Nu maksimum. Λ Meningkatkan dengan ketara mempengaruhi keberkesanan filem penyejukan (η) terutamanya di rantau sudut berbanding untuk ℓ dan Re. Analisis ketidakpastian dan analisis statistik keputusan berangka menunjukkan bahawa ramalan-ramalan dalam julat yang boleh diterima dan boleh dipercayai.

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I certify that a Thesis Examination Committee has met on 4 May 2012 to conduct the final examination of Asghar Pishgahi on his thesis entitled "Numerical Investigation of Laminar Flow and Thermal Characteristics of Tangential Cooling Air Jet in a Sudden Expansion Channel" in accordance with Universities and University Colleges Act 1971 and Constitution of the Universiti Putra Malaysia [P.U. (A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for the quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not currently, submitted for any other degree at Universiti Putra Malaysia or at any other institutions.

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ASGHAR PISHGAHI

Date: 4 May 2012

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