P25 Surface Heat Transfer Measurements Using a Thermographic Phosphor Imaging System

Mingking K. Chyu (mc47@andrew.cmu.edu; 412-268-3658)
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213

Abstract

The collective finding obtained from the present AGTSR project suggests that the thermographic phosphor (TGP) measurement technique developed at Carnegie Mellon is a very effective method for characterizing the surface heat transfer of a system with multiple driving temperatures. Its unique feature in resolving film effectiveness and local heat transfer coefficient simultaneously is unmatchable by any measurement approach for turbine cooling applications. As a result of collaboration with researchers in several ATS industrial partners, the present research focus is extended to exploit issues concerning heat transfer with interfacial leakage and its interaction with film cooling present in the vicinity. Such issues were unable to be resolved effectively by other experimental techniques in the past. Leakage is one class of turbine cooling problems which has been much disregarded, yet occurs in many locations within the turbine hot flow path, concerns the flow and heat transfer over component-to-component interfaces. Ideally, the interfaces are perfectly smooth transitions which present the least possible disruption, and hence also the least turbine losses. In reality, interfaces are subject to misalignment due to manufacturing tolerances and assembly, and so may present steps in the flow path having undesirable aerodynamic and thermal consequences. A better control of leakage on both manufacturing and operational fronts becomes essential as the targeted system performance increases.

The convective transport for the baseline geometry with interfacial leakage is a "three-temperature" problem, as the heat transfer in the system is driven by three temperature sources. The case is further complicated when film cooling is present in the gap vicinity - the system becomes a "four-temperature" problem. A four-temperature problem or a three-temperature problem is far more complex than its two-temperature counterpart. In the past year, significant effort has been devoted to analyzing the four-temperature problem and identifying key parameters that govern the thermal characteristics of the system. The local reference temperature for defining a viable heat transfer coefficient is expressed as a function of multiple film effectiveness. The results reveal that the amount of leaking flow as well as the gap geometry and orientation has profound effects on the overall film cooling performance.

Acknowledgments

This work is sponsored by the U.S. Department of Energy's Federal Energy Technology Center under Contract DE-FC21-92MC29061. The author would like to thank Dr. Lawrence P. Golan, Director, South Carolina Energy Research and Development Center and Dr. Daniel B. Fant, Research Manager, Advanced Gas Turbine Systems Research for their support of this research.

Surface Heat Transfer Measurements Using a Thermographic Phosphor Fluorescence Imaging System

Mingking K. Chyu

and

S.C. Yao

Dept. of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, PA 15213 - 3890

MOTIVATION & OBJECTIVES

- To Develop and Characterize a Thermal Imaging System Based on Thermographic Phosphorescence
- System performance must be comparable with or better than existing techniques; e.g. infrared, liquid crystals, sublimation analogy, etc.
- Potential for

  simultaneous measurement of temperature and heat flux

  very wide measurement range; cryogenics to turbine

  rapid unsteady or rotating phenomena

  microscale heat transfer

Project Accomplishments

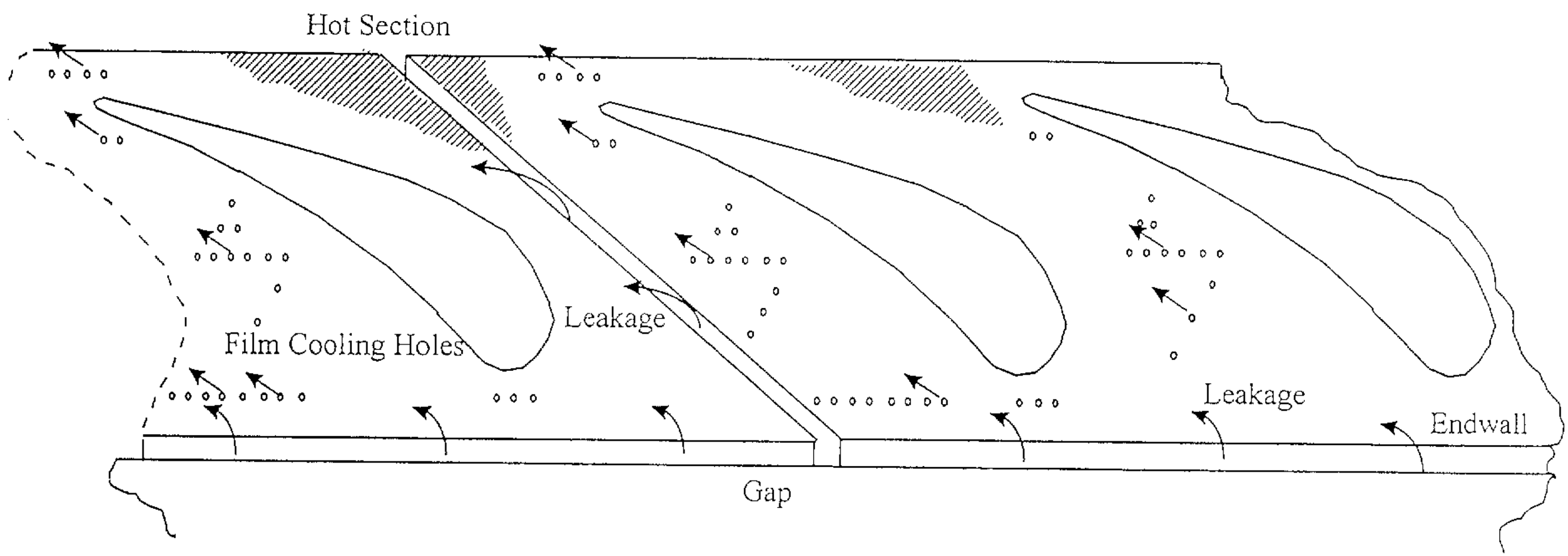
- Development of a laser-induced fluorescence imaging system based on thermographic phosophors (TGP)
- Fluorescent thermometry:

  LaS_2O_2:Eu (near room temperature)

  YAG:Dy (high temperature, 800 C tested, 1200 C potential)

- Development of optical heat flux gauge with demonstration studies
- Use of TGP for transient convective heat transfer tests, direct comparisons with liquid crystal results
- Use of TGP for multiple-temperature situation relating to film cooling around turbine passage endwall

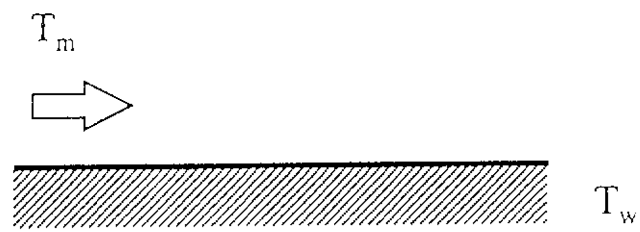
  Three-temperature: film cooling
  Four-temperature : film cooling interaction with endwall leakage


Hot Section
Leakage
Film Cooling Holes
Leakage
Endwall
Gap

Multiple Temperature Problems

$$q = h(T_r - T_w)$$

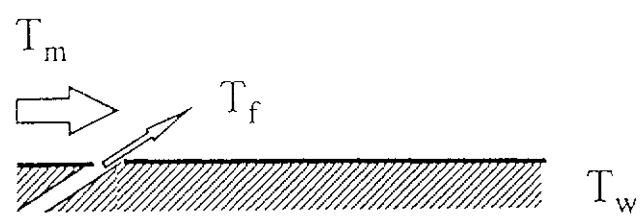
2-T Problem:



$T_r = T_m$

$h = ?$

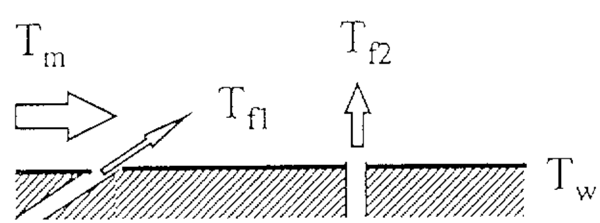
3-T Problem:



$T_r = ?$

$h = ?$

4-T Problem:



$T_r = ?$

$h = ?$

Data Reduction Principle

- local surface heat flux

$$q = h(T_r - T_m)$$

- film cooling effectiveness

$$\eta = (T_r - T_m)/(T_f - T_m)$$

- applying semi-infinite slab assumption

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2}$$

$$-k \frac{\partial T}{\partial z} = h(T_r - T_w), \quad \text{at } z = 0$$

$$T_w = T_i \quad , \quad \text{at } z = \infty$$

$$T_w = T_i \quad , \quad \text{at } t = 0$$

- the solution is

$$\frac{T_w - T_i}{T_r - T_i} = 1 - \exp\left(\frac{h^2 \alpha \cdot t}{k^2}\right) \operatorname{erfc}\left(\frac{h\sqrt{\alpha \cdot t}}{k}\right)$$

- using superposition, the transient test

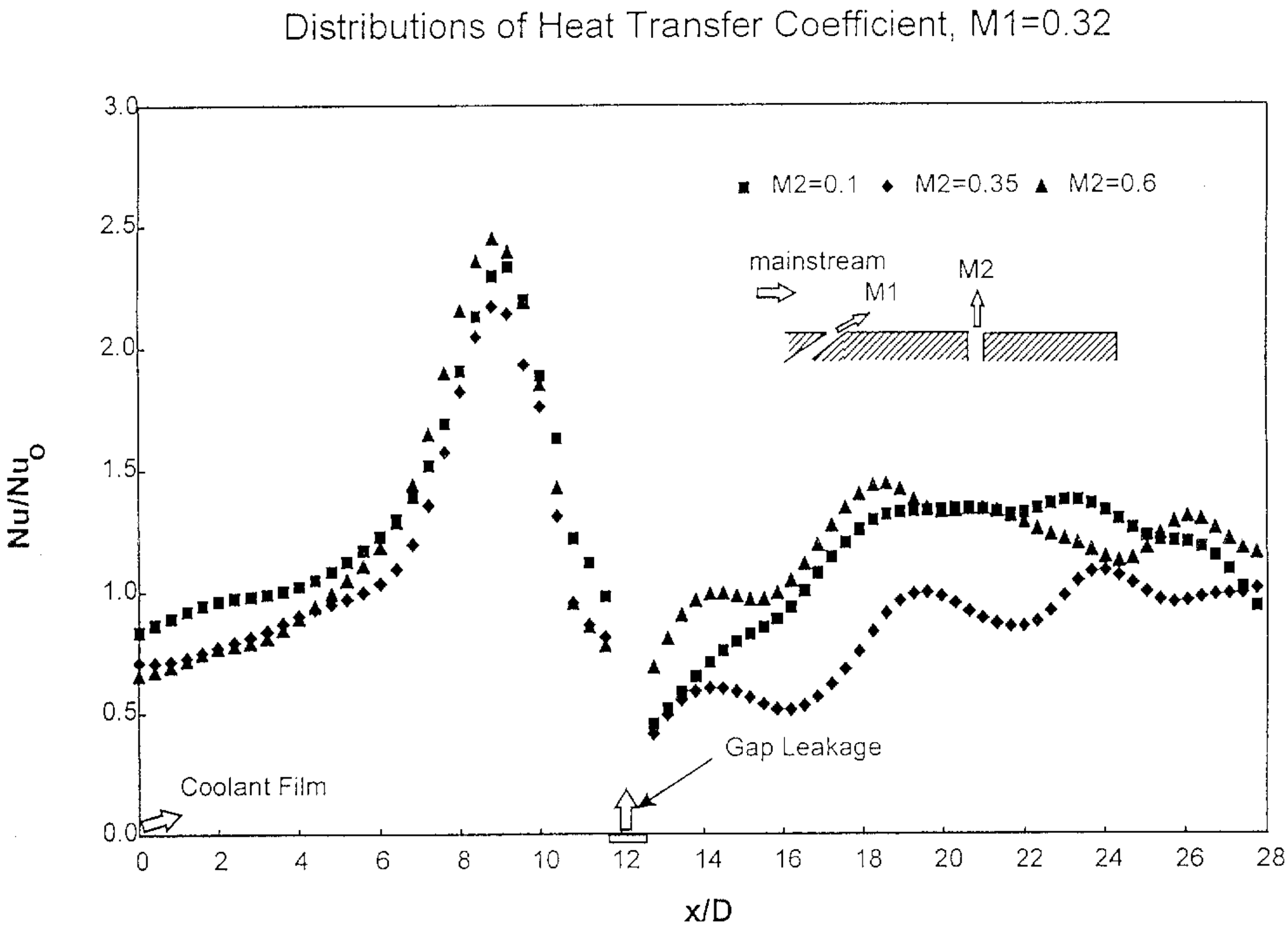
$$T_w - T_i = \sum_{j=1}^{N} U(t - \tau_j) \cdot \Delta T_r$$

where:

$$U(t - t_j) = 1 - \exp\left[\frac{h^2}{k^2} \alpha (t - t_j)\right] \operatorname{erfc}\left[\frac{h}{k} \sqrt{\alpha (t - t_j)}\right]$$

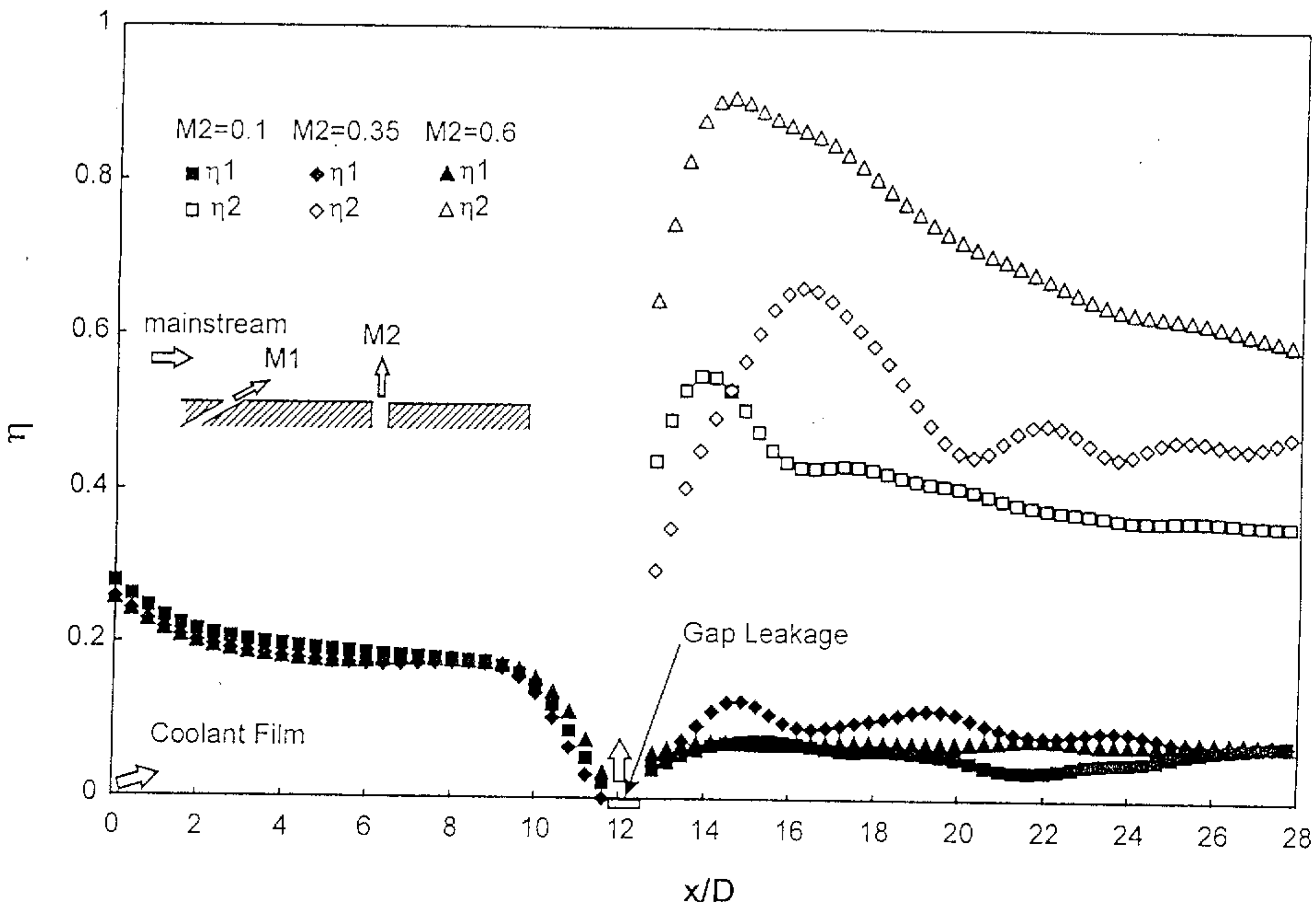
and

$$\Delta T_r = (1 - \eta) \Delta T_m + \eta \Delta T_f$$

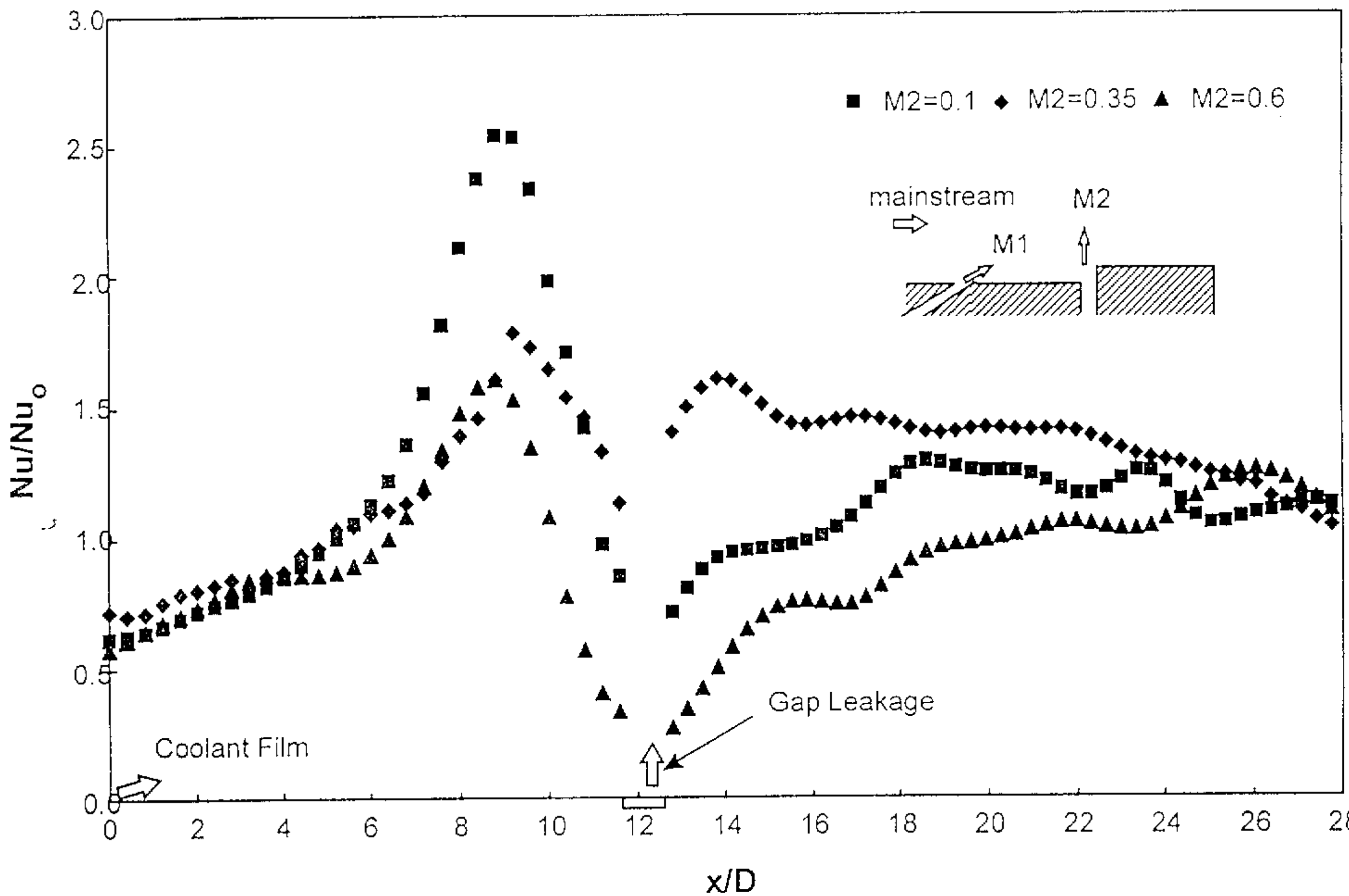


Distributions of Heat Transfer Coefficient, M1=0.32
M2=0.1
M2=0.35
M2=0.6
mainstream
M1
M2
Gap Leakage
Coolant Film
Nu/Nu_O
x/D
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

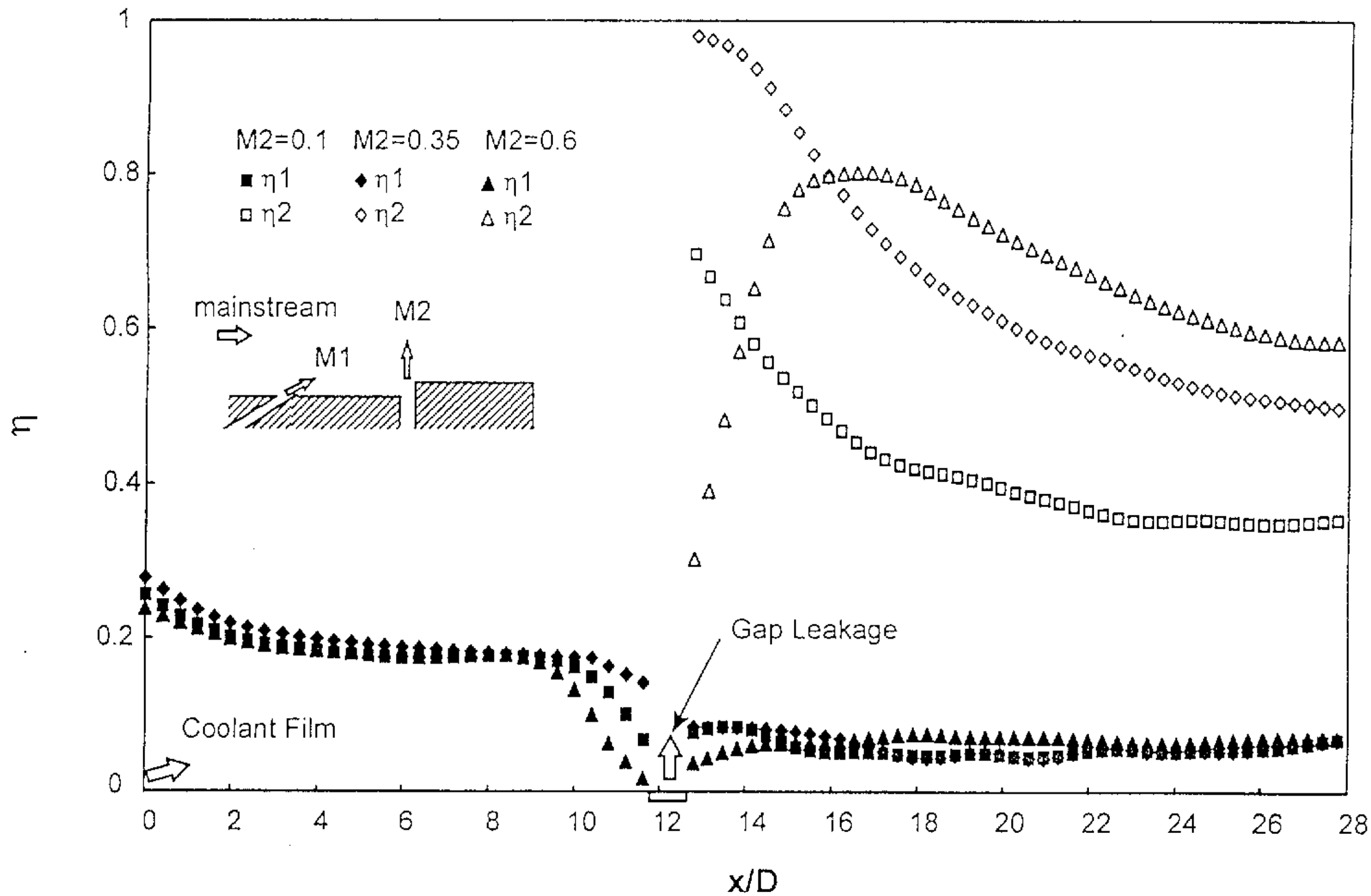
Effectiveness Distributions over a Flat Plate, M1=0.32



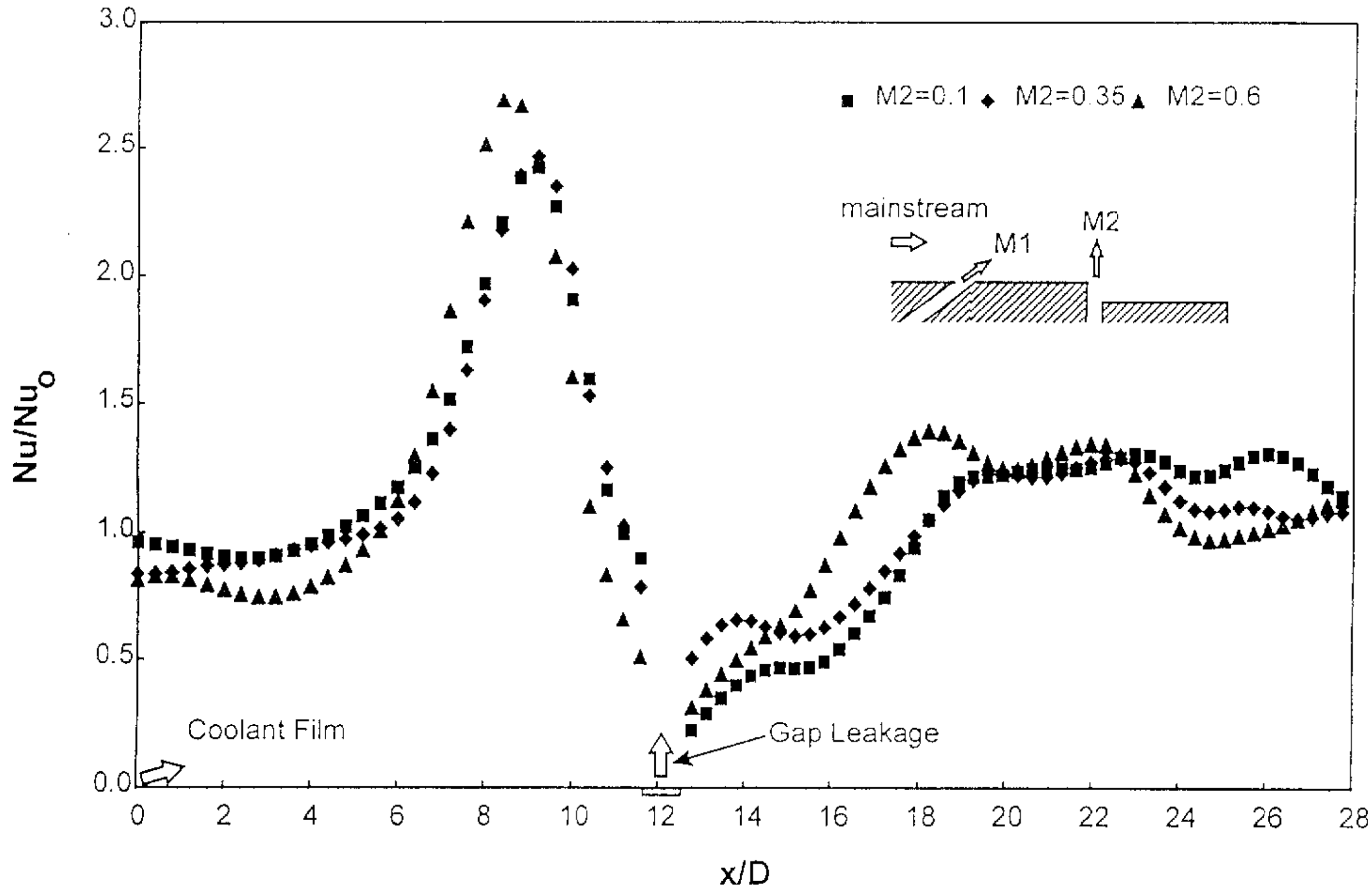
Distributions of Heat Transfer Coefficient, M1=0.32



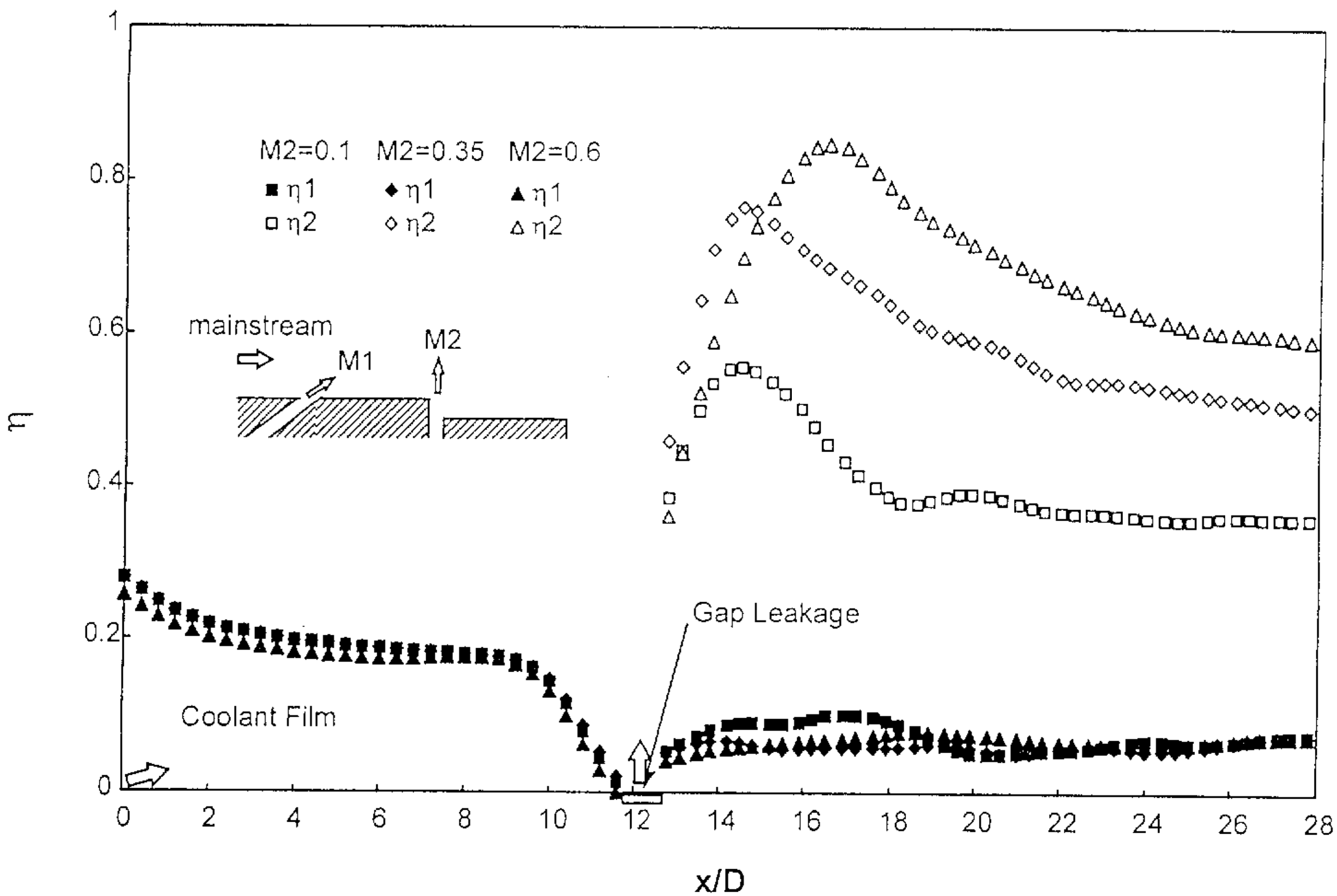
Effectiveness Distributions over a Forward-Facing Step, M1=0.32



Distributions of Heat Transfer Coefficient, M1=0.32



Effectiveness Distributions over a Backward-Facing Step, M1=0.32



Conclusions

- Successful development of a laser-induced fluorescence thermal imaging system based on thermographic phosphors (TGP)
- Potential demonstrated for high-temperature, high-speed applications
- The TGP-based optical heat flux sensor developed reveals excellent data quality in resolving local surface heat transfer
- The use of a TGP coated surface in conjunction with a transient condution model is very effective in determining the local heat transfer coefficient. Significant advantages over liquid crystals technique
- TGP is most capable of resolving complex heat convection problems with multiple reference temperatures, which exist often in gas turbine cooling systems
- Acquisition of detailed film cooling data in three-temperature and four-temperature systems