Project 1859 | February 2020

SJSU SAN JOSÉ STATE UNIVERSITY

MTI MINETA TRANSPORTATION INSTITUTE

Reducing NOx Emissions of Cargo Handling Equipment (CHE) with Humid Air Systems

Hamid Rahai, PhD
Jeremy Bonifacio, PhD

CSUTC California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

MINETA TRANSPORTATION INSTITUTE

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the four-university. MTI leads the four-university California State University Transportation Consortium funded by the State of California through Senate Bill 1.

MTI's transportation policy work is centered on three primary responsibilities:

Research

MTI works to provide policy-oriented research for all levels of government and the private sector to foster the development of optimum surface transportation systems. Research areas include: bicycle and pedestrian issues; financing public and private sector transportation improvements; intermodal connectivity and integration; safety and security of transportation systems; sustainability of transportation systems; transportation / land use / environment; and transportation planning and policy development. Certified Research Associates conduct the research. Certification requires an advanced degree, generally a Ph.D., a record of academic publications, and professional references. Research projects culminate in a peer-reviewed publication, available on TransWeb, the MTI website (http://transweb.sjsu.edu).

Education

The Institute supports education programs for students seeking a career in the development and operation of surface transportation systems. MTI, through San José State University, offers an AACSB-accredited Master of Science in Transportation Management and graduate certificates in Transportation Management, Transportation Security, and High-Speed Rail Management that serve to prepare the nation's transportation managers for the 21st century. With the active assistance of the California Department of Transportation (Caltrans), MTI delivers its classes over a state-of-the-art videoconference network throughout the state of California and via webcasting beyond, allowing working transportation professionals to pursue an advanced degree regardless of their location. To meet the needs of employers seeking a diverse workforce, MTI's education program promotes enrollment to under-represented groups.

Information and Technology Transfer

MTI utilizes a diverse array of dissemination methods and media to ensure research results reach those responsible for managing change. These methods include publication, seminars, workshops, websites, social media, webinars, and other technology transfer mechanisms. Additionally, MTI promotes the availability of completed research to professional organizations and journals and works to integrate the research findings into the graduate education program. MTI's extensive collection of transportation- related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

REPORT 20-03

REDUCING NOx EMISSIONS OF CARGO HANDLING EQUIPMENT (CHE) WITH HUMID AIR SYSTEMS

Hamid Rahai, PhD
Jeremy Bonifacio, PhD

February 2020

A publication of

Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 20-03	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Reducing NOx Emissions of Cargo Handling Equipment (CHE) with Humid Air Systems		**5. Report Date** February 2020 **6. Performing Organization Code**
7. Authors Hamid Rahai, PhD orcid.org/0000-0003-4171-466X Jeremy Bonifacio, PhD		**8. Performing Organization Report** CA-MTI-1859
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		**10. Work Unit No.** **11. Contract or Grant No.** ZSB12017-SJAUX
12. Sponsoring Agency Name and Address State of California SB1 2017/2018 Trustees of the California State University Sponsored Programs Administration 401 Golden Shore, 5th Floor Long Beach, CA 90802		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplemental Notes DOI: 10.31979/mti.2020.1859		

16. Abstract

The authors designed and tested a humid air system (HAS) for reducing NOx emissions of an LPG-powered forklift. The HAS uses distilled water and heat from the exhaust to generate steam that is injected into the intake air of the engine to increase humidity and thus achieve NOx reduction. Field tests with HAS have shown 2.2 ppm of NOx reduction with each percent increase in humidity of the intake air. A provisional patent based on the developed system has been filed.

17. Key Words CNG and LPG Engines, NOx Emissions, Humid Air System (HAS), Emission Control Technologies, Cargo Handling Equipment	**18. Distribution Statement** No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 12	**22. Price**

Form DOT F 1700.7 (8-72)

DOI:
10.31979/mti.2020.1859

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu

022320

ACKNOWLEDGMENTS

Funding for this research was provided by the State of California SB1 2017/2018 through the Trustees of the California State University (Agreement # ZSB12017-SJAUX) and the California State University Transportation Consorti-um. The authors thank Editing Press for editorial services, as well as MTI staff, including Executive Director Karen Philbrick, Ph.D.; Deputy Executive Director Hilary Nixon, Ph.D.; Graphic Designer Alverina Eka Weinardy; and Executive Administrative Assistant Jill Carter.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Sun-light driven chemical reactions in the lower part of the troposphere (a height of 10 km from ground) results in ground-level ozone and other photochemical oxidants. The reactions primarily involve volatile organic compounds (VOC) and nitrogen oxides (NOx). Ozone impacts respiratory tracts, hence increasing the incidence of asthmatic attacks and contributing to the development of lung cancer. Ozone also damages crops (reducing yields), causing major economic losses. Ozone can be generated locally or regionally and can also be transported over very long distances. Reducing NOx reduces ground-level ozone, with increased economic and health impacts.

Humid Air System (HAS) or fumigation has been used for reducing NOx emissions of diesel engines. Adding humidity to the intake air of diesel engines reduces combustion temperature and NOx emissions. It also cleans the engine and improves its longevity. In our previous application of HAS to a diesel engine we demonstrated that a more than 60% reduction in NOx emissions could be obtained with intake air at or near the saturation condition.[8] A subsequent study of the impact of HAS on a compressed natural gas (CNG) powered engine demonstrated similar results. [10]

In this study, we developed a system to generate steam from distilled water using engine exhaust heat and applied it to a CNG-powered cargo handling equipment in order to reduce its NO_x emissions. The study includes both laboratory and field testing. A Clark forklift, Model GM 3.0 LPG (liquid propane gas), was used for field testing. The laboratory test was performed on a PSI engine, Model GM 3.0, using compressed natural gas (CNG). The HAS includes an attachable exhaust pipe with coiled-tube insert that is used as a heat exchanger for generating steam, a pump with a solenoid valve for supplying distilled water to the coiled exhaust pipe, a mixing box for mixing intake air with steam. A feedback control system with temperature and humidity sensors was used for controlling supplied water and thus the amount of steam generated for increasing the humidity of the intake air. Results of both stationary engine and field tests indicate that maintaining the humidity of the intake air between 90% to saturation results in a significant reduction in NOx emissions. Both stationary engine tests and field testing indicate 2–3 ppm of NOx reduction per 1% increase in relative humidity.

I. BACKGROUND

The 2016 port of Los Angeles (POLA) inventory of air emissions divides maritime industry-related emissions into five categories: ocean-going vessels (OGV), harbor crafts, locomotives, heavy duty vehicles, and cargo handling equipment (CHE).[1] The largest annual contribution of NOx emission comes from the OGVs at over 3200 tons, followed by the heavy duty vehicles, locomotives, harbor crafts, and CHEs at approximately 1857, 780, 751, and 435 tons, respectively. NOx is one of the main ingredients involved in the formation of the ground-level ozone (smog) which could cause respiratory illnesses, especially in children and older adults and people with lung diseases. It also contributes to global warming. NOx reacts with other substances to form acid aerosols and subsequently acid rain which damages vegetation and contaminates rivers, impacting fish populations, causing increased nitrogen loading in water, and changing the aqueous chemical balance of nutrients used by aquatic plant and animal life with adverse impacts. It blocks transmission of light and thus impairs visibility. Ozone can be transported by wind, and its health impacts can reach far from its original source.

Over the past decade, due to the Port of Long Beach (POLB) and POLA's aggressive intervention programs, ports' emission contributions in the south coast basin have been reduced significantly. For POLA, the percentage of diesel particulate matter (DPM) has dropped from approximately 9% to below 5%, and the percentage of oxides of sulfur (SOx) has dropped from over 25% to less than 2.5%. However, there has not been significant overall reduction in NOx emissions, which have persisted at around 5%. Here, the authors developed and tested a humid air system for bringing about significant reductions in NOx emissions from CHEs' operation. The estimated contributions of CHE operation to the total annual NOx emissions is slightly higher than 6%. The CHE category surveyed at POLA includes 2202 pieces of equipment which includes yard tractors (48%), forklifts (23%), top handlers (10%), RTG crane (5%), side pick (1%), and 13% "others" which includes man lift, excavators, rail pushers, sweepers, bulldozers, and so on. The yard tractors' engines are 851 diesel, 17 LNG, and 180 propane, and the forklifts' engines are 118 diesel, 381 propane, 7 gasoline, and 8 electric. The focus in this work will be on propane-powered forklifts, with annual contributions to NOx emissions at 16.2 tons.

Humid air systems (HASs) or fumigation have been an effective approach in reducing diesel NOx emissions. In this method, water vapor is injected at the location of the intake air supplied to the engine cylinders. The process reduces the local temperature in the cylinder and raises the specific heat of the air–fuel mixture, which also contributes to the elimination of the hot spots in the engine's cylinders. With decreased temperature, NOx reduction is achieved. With an optimized system, fumigation could reduce NOx emission without significant increases in hydrocarbon emissions. Other benefits of this process include longer life of the engine components due to reduced cycle temperature and reductions in carbon deposits. Previous investigations of the impacts of humid air systems on diesel engines [2–6] or combustion flames have shown significant reductions in combustion temperature and up to 60% reduction in NOx emissions.

Rahai et al. and Farahani et al. have investigated the effects of humid air on the performance of a naturally-aspired three cylinder diesel engine with a low-sulfur diesel fuel.[7 8 9] The addition of the humidity to the intake air was performed with a variable steam generator using distilled water, where the relative humidity levels of the intake air were changed from the ambient conditions of 65% to 75% and 95% levels. The tests were performed at two approximate engine output break horse powers (BHP) of 5.9 and 8.9. Results showed approximately 3.7% and 22.5% reduction in NOx emissions when the relative humidity of the air was increased from 65% (the ambient relative humidity) to 75% and 95%, respectively. The addition of the humidity results in increases in the CO, CO2, and PM, by approximately 3.7%, 3.55%, and 14.9% at 5.9 BHP and 22%, 2.8%, and 9.3% at 8.9 BHP. There was no change in the brake specific fuel consumption (BSFC) at 5.9 BHP but there was about a 2.7% increase in the BSFC at 8.9 BHP. Their results indicate that for both mobile and stationary diesel engines, the humid air system is a viable option for attaining significant reduction in NOx emissions.

Recently, Rahai et al. investigated the effect of a humid air system on NOx and particulate matter (PM) emissions of a compressed natural gas (CNG) engine and natural gas combustion.[10] Results from their theoretical investigation of the natural gas combustion showed a NOx reduction of up to 80% with input air at 60% relative humidity (RH). For the experimental investigations, General Motors inline 4 cylinders, naturally aspirated engine with a maximum rated horsepower (HP) of 50.8 for natural gas fuel, was used. The engine was connected to a water-cycled dynamometer. NOx emission was measured by a Horiba portable emission analyzer model 250 and exhaust PM was measured using a dilution tunnel in conjunction with a cyclone with teflo filters. The experiments were carried out at four different horsepower values of approximately 5, 12.5, 25, and 37.5, and three relative humiditys (RH) of ambient (30%), 45%, and 60%. Results showed for each additional 15% increase in relative humidity, there was nearly a 10% reduction in NOx emission.

The PM emissions increased with the addition of relative humidity, especially at low HPs. With increasing HP, the PM augmentation was reduced significantly, and at 37.5 HP, the ratios of PM emitted at 45% and 60% RH to the corresponding ambient baseline values (at 30% RH) were near 2.0.

The main objective of the current investigation was to design and field test a humid air system for reducing NOx emission of a CNG-powered forklift.

II. EXPERIMENTAL SET-UP

HUMID AIR SYSTEM (HAS)

Figure 1 shows the stationary compressed natural gas-powered engine that was used to initially test the humid air system (HAS). Figure 2 shows the schematic of the injection system. The engine is a General Motors inline four-cylinder, naturally aspirated engine with a maximum rated horsepower (HP) of 50.8 for natural gas fuel. The engine is connected to a water-cycled dynamometer from Land & Sea which is equipped with automated data acquisition for engine performance tests. NOx emission was measured using a Horiba portable emission analyzer, Model 250, which uses non-dispersive IR detection for CO, SO_2, and CO_2; chemiluminescence (cross-flow modulation) for NO_x; and a galvanic cell or an optional zirconium oxide sensor for O_2 measurements. The engine was tested with ambient humidity (baseline), added humidity using a vapor machine, and finally added humidity with HAS. A Rosco Vapor machine with distilled water was used to generate the added fog to the intake air. In all cases, the humidity level of the intake air before and after adding humidity was measured with two TSI VelocCalc model 9565-P anemometers.

The HAS includes a tubular coiled heat exchanger, placed at the outlet of the engine exhaust, a tank of distilled water, a pump that transfers the distilled water through a solenoid valve into the heat exchange coil to generate steam from the exhaust heat, and delivery of the steam into the intake mixing box that increases the air intake humidity level. An iterative process has been performed to identify the appropriate design and dimensions of the tubular coiled system to minimize exhaust blockage. A humidity sensor is placed in the mixing box to monitor and maintain humidity level to near saturation. A feedback control system adjusts the solenoid valve opening per the humidity level in the mixing box.

Figure 1. The Compressed Natural Gas (CNG) Engine with Humid Air System

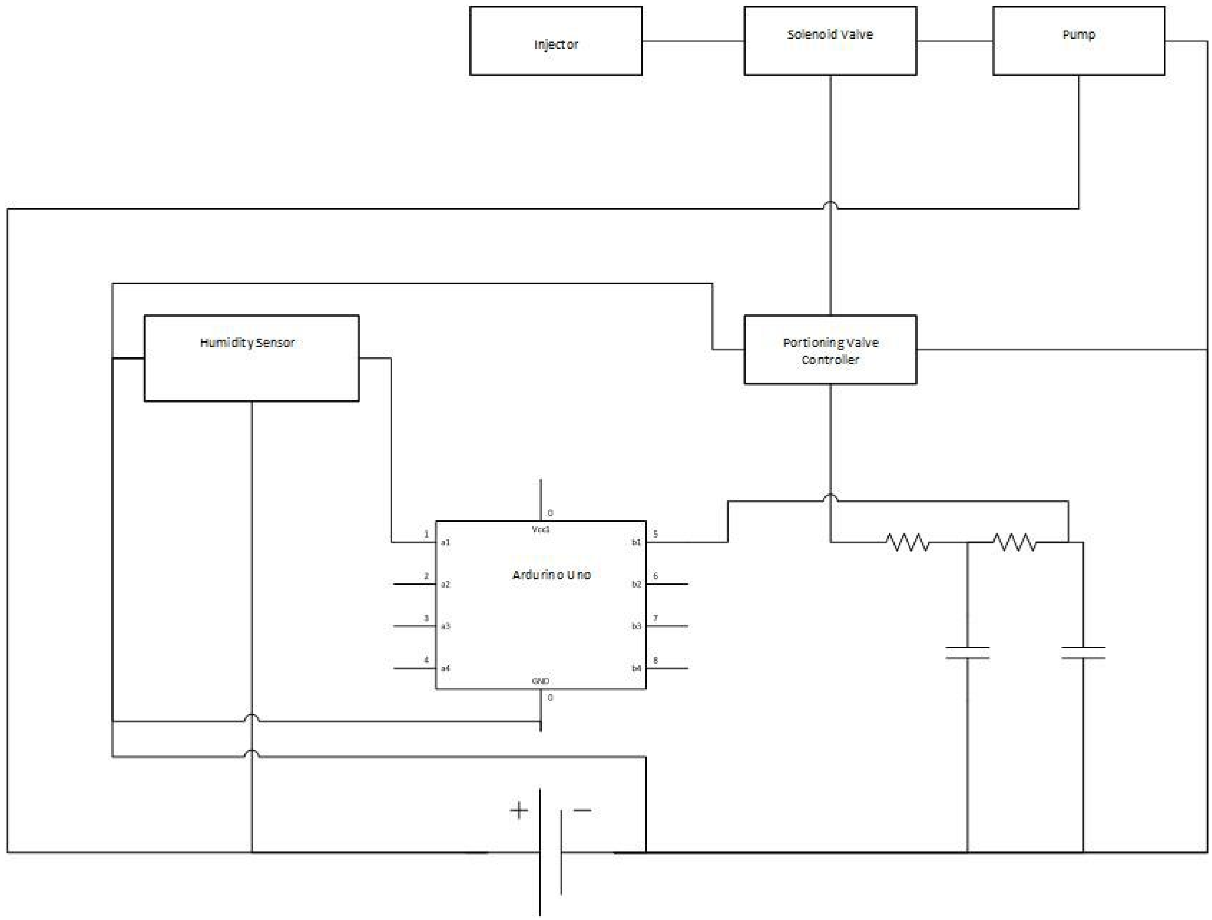

Figure 2. Schematics of Humid Air Injection System

FIELD TEST OF HAS ON A CNG FORKLIFT

A Clark forklift, Model GM 3.0 LPG, was used for field tests. Figure 3 shows the forklift with attached Humid Air System (HAS). The engine was of the same model and specifications as the one that was used for stationary test in section 2.1, with the exception that liquid propane was used as the fuel. The tests were conducted with both lifting a cargo of steel brackets totaling 2185 lbs. and running at full throttle and load. In both cases, the exhaust temperature exceeded the water boiling temperature and thus it was possible to have continuous steam flow for input to the mixing box to increase the humidity of the intake air to achieve NOx reduction.

For NOx measurement, a portable Enerac micro emission analyzer, Model 500, was used. The unit is used to measure carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and oxygen from stationary and mobile engines. The range of measurement for these gases are:

- OXYGEN Electrochemical cell. Life 2 years. Range: 0–25% by volume. Resolution: 0.1%. Accuracy: 0.2%.
- NITRIC OXIDE (NO) Electrochemical cell. Life 2 years. Range: 0–2000 ppm.

Resolution: 1 ppm. Accuracy: 4% of reading (±5 ppm when measuring less than 100 ppm).

- NITROGEN DIOXIDE (NO_2) Electrochemical cell. Life 2 years. Range: 0–1000 ppm. Resolution: 1 ppm. Accuracy: 4% of reading (±5 ppm when measuring less than 100 ppm).

- CARBON MONOXIDE Electrochemical cell. Life 2 years. Range: 0–2000 ppm (optional ranges available: 10000 & 20000 ppm). Resolution: 1 ppm. Accuracy: 4% of reading (±5 ppm when measuring less then 100 ppm).

- SULFUR DIOXIDE Electrochemical cell. Life 2 years. Range: 0–2000 ppm. Resolution: 1 ppm. Accuracy: 4% of reading (±5 ppm when measuring less then 100 ppm).

Figure 3. Clark Forklift with HAS

III. RESULTS AND DISCUSSION

Table 1 shows the test results for the stationary engine. For all tests, the horsepower was maintained at nearly 50% of the rated power, namely, at 27. This was sufficient to test the engine with HAS; as for higher horsepower, engine vibration posed a significant problem in maintaining steady state operation. Results for the baseline and with steam generated from the fog machine are in accordance with our previous investigation, reducing NOx by nearly 20% with increasing humidity by more than 42%.[10] The NOx ppm drops from 452 to 366, resulting in a ppm NOx reduction per percent humidity, ppm(NOx)/%Hum, of 2.02. When HAS was used, the authors were able to maintain saturation conditions (100% humidity) during the test, and further reduction in NOx was obtained which resulted in ppm(NOX)/%Hum of 3.32. The corresponding values of ppm(NOx) per gram distilled water were 8.95 and 11.76, respectively. With added humidity, CO was increased by 23% and 29%, respectively, using the fog machine and HAS. The increases in CO per percent increase in humidity, ppm(CO)/%Hum, were 3.6 and 5.2, respectively.

When HAS was used, while the authors were maintaining saturation at the engine air intake, there was condensation in the mixing box due to a drop in temperature, and thus it is expected that the amount of water required to maintain saturation would be reduced. However, the benefit of excess steam was that the engine could be supplied with saturated humid air continuously which resulted in a significantly higher NOx reduction at 27%.

Table 1. Stationary Engine Test Results

Natural Gas Engine (50HP Max)	Baseline	Fog Machine	HAS
Power (hp)	27	27	27
Humidity level (%)	61.2	98.3	100
Ambient humidity (%)	61.2	55.9	63.9
Ambient temperature (°F)	78.4	75.8	78.4
Air flow rate (cfm)	41	41	41
NOX (ppm)	452	366	332
CO (ppm)	6.7	8.24	8.65
Mass dry air (g/min)	1395	1395	1395
Mass humidity (g/min)	0.	9.6	10.2
Mass fuel (g/min)	132	132	132
Humidity–Fuel mass ratio (%)	0.	7.3	7.7
Ratio of NOx to baseline	1.0	0.81	0.73
Ratio of CO to baseline	1.0	1.23	1.29
ΔNOx(ppm)/Δ%Humidity	N/A	2.02	3.32

Table 2 shows similar results for the field test for the engine load with full throttle. This condition is very similar to the stationary engine loading using a dynamometer. The horsepower is estimated from the power rating of the hydraulic pump used to load the engine while the forklift was stationary. Nearly a 70% reduction in NOx emissions was obtained with HAS at 90% relative humidity. The ppm(NOx)/%Hum is 2.2, which is close to the case of stationary engine with steam generated from the fog machine. With added humidity, the stack temperature dropped from 616°F to 274°F, resulting in a 17% increase in CO. The ppm(CO)/%Hum is approximately 3.5, which is again close to the corresponding results with the fog machine on the stationary engine.

With liquid propane and the engine in operation, it was still possible to maintain an exhaust temperature above the boiling temperature of water in order to generate the necessary steam to reduce NOx emissions. However, it was difficult to increase humidity and maintain saturation conditions. With added humidity and engine cool-down, it is expected that the humidity from the generated steam will stay between 90% and 100%, maintaining a healthy NOx reduction.

Table 2. Field Test with Forklift

Forklift Test (67 HP Max)	Baseline	HAS
Power (HP)	30.8	30.8
Humidity level (%)	55.2	90
Ambient humidity (%)	55.2	55.2
Ambient temperature (°F)	69.8	69.8
Stack temperature (°F)	616	274
Air flow rate (cfm)	63	63
NOX (ppm)	117	40
CO (ppm)	58	68
Mass dry air (g/min)	2140	2140
Mass humidity (g/min)	0.	22
Mass fuel (g/min)	203	203
Humidity–Fuel mass ratio (%)	0.	10.8
Ratio of NOx to baseline	1.0	0.34
Ratio of CO to baseline	1.0	1.17
ΔNOx(ppm)/Δ%Humidity	N/A	2.2

These results indicate that, with the addition of steam, the heat capacity of the intake air is increased, resulting in reduced combustion temperature. Similar results have been found by Riom et al. in reducing NOx emissions of a turbo-charged diesel engine using a humid air motor concept.[11]

Assuming an average of 60% efficiency in reducing NOx emission for the developed HAS, nearly 10 tons of NOx reduction could be obtained annually by using data from the POLA report on their annual inventory of air emissions and by incorporating HAS into existing propane-powered forklifts. The system could also be incorporated into diesel, propane, and LNG powered CHE, which could result in significant increases in annual NOx reduction.

The current results provide a baseline parameter, /% NOx reduction per % increase in humidity, which allows the system to be scalable for applications to larger CNG and LNG engines, especially when freight transport is considered. The system could also be adapted to existing vehicles as well as incorporated into design of new engines. With the adaptation of this system to both gas and diesel-powered engines, significant reductions in NOx emissions could be obtained, resulting in improved air quality, health, and the economy.

IV. CONCLUSION

A humid air system (HAS) was designed and field tested to reduce the NOx emissions of CNG-powered engines. The system used distilled water and heat of exhaust to generate steam, injected at the intake air of the engine to increase humidity and reduce temperature and NOx emission. The system includes a pipe with a coiled-tube insert that is attached to the exhaust. A water pump connected to a solenoid valve supplies distilled water from a container to the exhaust coil, generating steam that is fed to a mixing box at the engine air intake in order to increase intake air humidity. A feedback control system controls the solenoid valve opening to adjust the water flow rate for maintaining humidity level between 90% to saturation. Results of the field test with a Clark forklift, Model GM 3.0 LPG, show nearly a 70% reduction in NOx emission with 90% relative humidity at the intake air. The ppm NOx reduction per percent humidity was 2.2. Overall results including results from the stationary engine tests indicate that between 2–3 ppm NOx reduction could be obtained per 1% increase in humidity in the intake air. These results indicate the significant potential of HAS for reducing the NOx emissions of LPG- and CNG-powered cargo handling equipment at the ports.

ENDNOTES

1. Port of Los Angeles Inventory of Air Emissions-2016. Technical Report APP# 160825-520 A. July 2017.

2. Richie, A., De Jonge, E., Hugi, C., and D. Cooper. “Service Contract on Ship Emissions: Assignment, Abatement, and Market-Based Instruments.” Final Report. Entac, United Kingdom, 2005b.

3. Takasaki, K., T. Takaishi, H. Ishida, and K. Tayama. “Direct Water Injection to Improve Diesel Spray Combustion.” ICES 2003-554, 2003 Spring Technical Conference of the ASME Internal Combustion Engine Division, Salzburg, Austria, May 11–14, 2003: 27–34.

4. Radloff, E., and C. Gautier. “Diesel Engine NOx Reduction Using Charge Air Water Injection.” ICEF2005-1235, ASME Internal Combustion Engine Division Fall Technical Conference, Ottawa, Canada, September 11–14, 2005: 55–66.

5. Park, H. K., S. H. Ghal, B. S. Kim, K. D. Kim, and J.S. Kim. “NOx Reduction of a Medium Speed Diesel Engine Using a Charge Air Moisturizer System.” ICEF 2006-1548, ASME Internal Combustion Engine Division Fall Technical Conference, Sacramento, CA, November 5–8, 2006: 25–29.

6. Zhao, D., H. Yamashita, T. Furuhata, and N. Arai. “Analysis of Combustion Characteristics of Coaxial Jet Diffusion Flame with Steam Addition.” *Journal of Propulsion and Power* 16 (2000): 552–556.

7. Rahai, H. R. “Development and Assessment of a Humid Air System for Diesel NOx Reduction.” Final Report, SCAQMD, September 2009.

8. Rahai, H. R., E. Shamloo, and J. Bonifacio. “Investigations of the Effect of a Humid Air System on Diesel NOx and PM Emissions of a Small Diesel Engine.” Paper No. 2011-01-0692, 2011 SAE International Conference, Detroit, MI, April 2011.

9. Farahani, B., H. R. Rahai, R. Lo, and S. Faraji. “Experimental Investigations of the Effects of a Humid Air System and an Exhaust Scrubber on Diesel Emissions.” 5th International Urban Freight Conference, Long Beach, CA, October 2013 (I-NUF 2013).

10. Rahai, H., Y. Lee, N. Rahimi, and K. Gada. “Investigations of the Effect of Humid Air on NOx and PM Emissions of a CNG Engine.” SAE Paper no 2017-01-0783, Society of Automotive Engineers, March 2017.

11. Riom, E., Larsson, LO. & Hagström, U. MTZ Worldw (2002) 63: 10. https://doi.org/10.1007/BF03227539.

ABOUT THE AUTHORS

HAMID RAHAI, PH.D.

Dr. Hamid Rahai is a professor in the Departments of Mechanical and Aerospace Engineering & Biomedical Engineering and is Associate Dean for Research and Graduate Studies in the College of Engineering at CSULB. He has taught various classes at the undergraduate and graduate levels in the areas of fluid dynamics, thermodynamics, heat transfer, instrumentation, numerical methods, and turbulence. He has supervised over 65 M.S. theses and projects and Ph.D. dissertations and has published more than 90 technical papers. He has received in excess of 8 million dollars in grants and contracts from the National Science Foundation, Federal Highway Administration, California Energy Commission, California Air Resources Board, Port of Los Angeles, Caltrans, Boeing Company, Southern California Edison, Long Beach Airport, and Long Beach Transit, among others. He has been granted a patent for the development of a high-efficiency vertical axis wind turbine (VAWT) and another patent with Via Verde Company on wind turbine apparatuses. He also has pending patents related to a new diagnostic system for lung diseases using CFD, a new conformal vortex generator tape for reducing wing-tip vortices, and pending patents based on previous MTI-funded research into reducing drag of trailer trucks with rotating cylinders as well as the current study, reducing NOx emissions of gas-powered engines using a humid air system. For the past 26 years, he has been a consultant to local energy and aerospace industries. Dr. Rahai is the recipient of several scholarly and creative activities awards (RSCA), including the 2012 CSULB Impact Accomplishment of the Year in RSCA Award, the 2002–2003 CSULB Distinguished Faculty RSCA Award, and the 2004 Northrop Grumman Excellence in Teaching Award. In 2014, Dr. Rahai received the Outstanding Engineering Educator Award from the Orange County Engineering Council in California, and in 2019 he was inducted as a senior member of the National Academy of Inventors (NAI).

JEREMY BONIFACIO, PH.D.

Dr. Jeremy Bonifacio is a lecturer and a research associate at the Center for Energy and Environmental Research & Services (CEERS) in the College of Engineering at California State University, Long Beach. He has been involved in various projects at CEERS related to emission control technologies and mitigations along with various aerodynamics and indoor air quality projects. He is a co-owner of two provisional patents and author of ten technical publications.

PEER REVIEW

San José State University, of the California State University system, and the Mineta Transportation Institute (MTI) Board of Trustees have agreed upon a peer review process required for all research published by MTI. The purpose of the review process is to ensure that the results presented are based upon a professionally acceptable research protocol.