

SYNTHESIS, CHARACTERIZATION OF NANOSIZED SUPPORTED CERIA-BASED MIXED OXIDES FOR CATALYTIC APPLICATION

Synopsis

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Lakshmi Katta, M.Sc.

Indian Institute of Chemical Technology

Hyderabad – 500 607, India

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Over the past few years environmental legislation has imposed increasingly stringent targets for permitted levels of atmospheric emission. From the environmental point of view, CeO_2 , a non-stoichiometric rare-earth oxide, has received much attention in the recent past since it is expected to remediate such type of problems. In addition, it is also widely employed as a promoter for various applications including three-way catalysis (TWC) for automotive exhaust gas conversion [1-5], cracking of heavy oil [6], methane reforming with CO_2 and/or with steam [7,8], water-gas shift reaction [9,10], removal of soot from diesel engine exhaust [11], removal of organics from wastewaters [12], fuel cell processes [13-15], dehydration of alcohols etc. Ceria (CeO_2) is an important inorganic material stable from room temperature to its melting point (2673 K). In its most stable phase, bulk CeO_2 adopts a fluorite-type $Fm\bar{3}m$ crystal structure in which each metal cation is surrounded by eight oxygen atoms. The driving forces that make ceria is of great significance and serious interest for researchers are its two important functions on which the applicability of CeO_2 depends: (i) the redox couple (Eq. 1), $\text{Ce}^{4+}/\text{Ce}^{3+}$ with its ability to shift between CeO_2 and Ce_2O_3 under oxidizing and reducing conditions respectively, and (ii) elevated oxygen transport capacity by ease of formation of labile oxygen vacancies [16-18].



However, pure ceria have proved with limited applicability under high temperature treatments. Recent studies have shown that these redox properties can be significantly fine-tuned if additional elements are introduced into lattice by forming a solid solution [19]. The combination of two metals in an oxide can lead to novel structural and electronic properties of the final oxide, consequently favouring its catalytic activity and selectivity. In some cases, cations in a mixed metal oxide can also cooperatively catalyze different steps of a chemical process. At a structural level, a dopant ion facilitates defect formation within the oxide host by generating stress into the lattice. Introduction of elements with different size and/or charge resulting in the formation of a fluorite-structured material like CeO_2 modifies several features including structural defects in association with the bulk oxygen transport properties as a result enhanced catalytic activities even at moderate temperature [20]. Such changes in the structure of ceria also confer new properties to the catalysts, such as better resistance to structural and textural modifications under civior temperature treatments [21,22]. The dopant ion selection obviously plays an important role in modifying the chemical and physical properties of the produced mixed oxide. For instance, the concentration of oxygen vacancies that are produced during the doping of ceria depends on the

oxidation state of the dopant ion and the mobility of the oxygen vacancy/oxide ion depends on the association energy of the dopant ion with the oxygen vacancy. If the additive is aliovalent cation (M^{2+}/M^{3+}) then the oxygen vacancies can be introduced due to charge compensation mechanism and thus storage and release of oxygen increases. On the other hand, for isovalent cation the oxygen vacancy/oxide ion migration aids from the strain and distortion due to mismatch of the ionic radius of the dopant and Ce-ions in the substituted sample. Even though, isovalent cation doping especially Zr^{4+} lead to a thermally stable solid solution, the problem with Zr^{4+} is that it induces very limited concentration of oxygen vacancies and, thus, has a moderate effect on the redox properties of the system under oxidizing environment [23]. Therefore, the oxygen vacancy concentration and concomitant oxide ion conductivity can be increased through the lower-valent metal ion substitution. To improve this aspect, one can try doping of ceria by divalent dopant ions like Ca. However, Ca incorporated ceria samples are thermally less stable and prone to phase segregation due to significant drop in the strain and increase in the activation energy for the oxide ion/oxygen vacancy migration owing to defect association [23-26]. For technological applications at high temperature, one wants a dopant that introduces a reasonable amount of 'O' vacancies in the lattice of ceria and produces a mixed-metal oxide that has a high thermal stability. The compromise between these two properties depends on a significant number of variables. In any case, doping with Zr or Ca fully satisfies only one of these two requirements [27-32]. Doping with M^{3+} may be a solution to this complex problem.

The performance of ceria for various applications can be enhanced mainly by its doping with small concentrations of cations in particular lower valent cations (M^{3+}) like Gd, Sm, Y, La, Nd, Lu, etc [33]. Trivalent ions lower the energy barrier for oxygen ion migration through the lattice by creation of the oxygen vacancies at the expense of charge neutralization by means of vacancy compensation mechanism. The vacancies created in the anion sublattice by the presence of M^{3+} favour the reduction of Ce^{4+} cations [34,35], offering the possibility to use such materials as components for improved exhaust catalysts [36,37]. In other words, the presence of the trivalent cations in the formulation of the mixed oxides could be helpful in promoting the redox cycling of the cerium cations ($Ce^{4+} \leftrightarrow Ce^{3+}$) that can take place as a function of the composition of the exhaust gases leaving the engine. The increased ability for its reduction under milder conditions [34,35] makes these materials as interesting candidates for relieving emission problems during cold start operation of vehicles [38]. To address the above mentioned points and particularly to investigate the role of

aliovalent dopant ion La^{3+} in modifying the catalytic activities for various reactions, we describe synthesis and characterization of a fluorite structured ceria-lanthana mixed-oxide and correlated the characterization results with the activity studies.

However, the unsupported oxides are susceptible to a fall in the surface area due to sintering and it leads to a decrease in the stability of the structure during high temperature applications thereby losing its oxygen buffering capacity [39]. In order to exploit them without losing their unique redox features, it is very essential to synthesize nanosized materials where the active phase is stabilized over a stable inert support. In heterogeneous catalysis, catalytic activity scales with surface area. Hence, maximum dispersion of the particles is of extraordinary importance which makes the production of nanoscaled catalysts very tempting. The nanoparticle configurations are interesting from a practical viewpoint also as most of the applications are surface-sensitive, and a high surface-to-volume ratio in addition to improved redox properties, related to oxygen vacancy generation, can be reached by using nanosized materials.

Highly dispersed active oxides deposited on the surface of an inert support have been intensively studied for many years, mainly due to their applications as catalytic systems [39]. The essential requirements of a better support are nonreactivity with the dispersed phase and high specific surface area [40]. The catalytic performances of supported metal oxide catalysts are determined by many parameters, the most important being the metal oxide loading, pretreatment conditions, molecular structure, electronic structure, and support oxide type and composition [41]. Currently, ceria-based systems are usually supported on transition aluminas and titania, with the aim of achieving better dispersion of the active phase and improvement of the oxygen exchange rate. Silica is another most widely available supports with excellent chemical resistance, thermal stability, and high specific surface area, which can enhance dispersion and thereby catalytic activity of the dispersed active oxides [40].

Motivated by the unique and favourable characteristics of ceria-based materials for various catalytic applications, a systematic and comprehensive investigation was undertaken against the above background. In this study, ceria-lanthana and a series of catalytically important supported nanosized ceria-lanthana [$\text{CeO}_2\text{-La}_2\text{O}_3/\text{M}_x\text{O}_y$; ($\text{M}_x\text{O}_y = \text{Al}_2\text{O}_3, \text{SiO}_2, \text{and TiO}_2$)] solid solutions possessing high specific surface area, better thermal stability, superior sintering resistance, and desired redox properties have been synthesized. The thermal and structural stability of the supported ceria-based solid solutions are strongly influenced by the synthetic

methodology. In this study, soft chemical routes namely coprecipitation and deposition coprecipitation techniques were adopted for preparation of unsupported and supported mixed oxides respectively. Even though coprecipitation, surfactant assisted synthesis, and hydro thermally derived samples exhibit high surface area, severe loss of surface area occurs during high temperature treatments. Stabilization of nanoparticles of ceria-lanthana solid solutions on another oxide support such as alumina, colloidal silica or titania could represent a suitable way to overcome the drawbacks associated with unsupported mixed oxides. The prepared samples were further subjected to thermal treatments from 773 to 1073 K in order to understand the nano-structural evolution and physicochemical characteristics of these complex oxide systems. Various physicochemical characterization techniques namely, thermal analysis (TG-DTA), X-ray diffraction (XRD), transmission electron microscopy (TEM), laser Raman spectroscopy (LRS), UV-visible diffuse reflectance spectroscopy (UV-vis DRS), X-ray photoelectron spectroscopy (XPS), temperature programmed reduction (TPR), and BET surface area (SA) were employed to investigate these oxide systems. All the synthesized catalysts were evaluated for the potential oxygen storage capacity (OSC), soot oxidation and CO oxidation reaction. A few of the catalytic systems were also evaluated for the selective dehydration of 4-methylpentan-2-ol. Thus, the thesis primarily deals with the synthesis, characterization and activity of various unsupported and supported ceria-lanthana solid solutions aiming at the enhancement of performance in terms of thermal stability and catalytic point of view. The thesis has been organized into six individual chapters.

Chapter 1 comprised of a thorough literature survey on nanostructured metal oxides with special emphasis on cerium oxide and its composite oxides including structural, redox properties, and potential applications in catalysis with relevant references. A short introduction to the application of nanostructured metal oxides to different catalytic processes is also included. Importance of supported ceria-based materials has been discussed at length in this chapter. The main objectives and the scope of the present investigation are also clearly outlined.

The experimental procedures and the techniques employed in this investigation are described in **Chapter 2**. The details pertaining to the preparative methodologies employed to obtain the unsupported and supported ceria-lanthana solid solutions are presented with appropriate references in this chapter. The experimental details related to BET SA, TG-DTA, XRD, LRS, UV-vis DRS, XPS, and TPR are given with necessary theoretical background. The experimental aspects of the potential OSC

measurements, soot oxidation, CO oxidation reaction, and selective dehydration of 4-methylpentan-2-ol are also described in detail in this chapter. Each of these mixed oxides was shown to be a solid solution based on shifts in the lattice parameter obtained using XRD.

Chapter 3 deals with the preparation and intensive characterization of CeO₂–La₂O₃ mixed oxide by various spectroscopic and non-spectroscopic techniques and the evaluation of the catalyst system for OSC and CO oxidation activity. The CeO₂–La₂O₃ (8:2 mole ratio based on oxides) catalyst was prepared by an aqueous coprecipitation method. The sample was subjected to heat treatments from 773 to 1073 K to have information on its thermal stability. The XRD results suggest that the CeO₂–La₂O₃ sample primarily consists of nanocrystalline cubic Ce–La oxides with composition Ce_{0.8}La_{0.2}O_{2.8} over all the calcination temperatures. The samples are thermally quite stable and no phase segregation was observed up to the calcination temperature of 1073 K. The Raman measurements revealed the existence of cubic ceria-lanthana phase and establish the generation of defects in the lattice leading to the formation of oxygen vacancies. The XPS line shapes and the corresponding binding energies indicated that the Ce and La present in 3+, 4+ and 3+ oxidation states, respectively. The TEM-HREM results confirmed that the Ce-La-oxide nanocrystals have average particle dimension of ~8-15 nm when treated at 773 K, and there was a nominal increase in the particle size upon subjecting the catalyst system to 1073 K. The experimental images revealed that the Ce-La-oxides are mainly in the cubic geometry. The UV-vis DRS measurements confer information about Ce⁴⁺ ← O²⁻ and Ce³⁺ ← O²⁻ charge transfer transitions. The reducibility of the system was studied with the help of TPR measurements. The reduction temperature of the Ce-La-oxide was observed to be lower than that of the pure ceria and exhibited better redox properties even after severe heat treatment. The OSC of the resultant solid solution, measured by a thermogravimetric method, is found to be quite high thereby leading to remarkable CO oxidation activity (100% conversion at 740 K). The results are correlated well with the structural characterization data. All the results pertaining to CeO₂–La₂O₃ catalysts are compiled in this chapter.

Chapter 4 deals with the preparation, structural evolution, and catalytic activity (OSC and CO oxidation) of CeO₂–La₂O₃/TiO₂ samples. The CeO₂–La₂O₃/TiO₂ composite oxide (8:2:10 mole ratio based on oxides) was obtained by a deposition coprecipitation method. The addition of titania resulted into enhancement of surface area of the final catalyst. In this case, the XRD results suggest that the mixed oxide

calcined at 773 K primarily consists of poorly crystalline mixed oxides of Ce-La a better crystallization of these oxides occur with increasing calcination temperature while the crystallinity of titania was not changed much in accordance with the active component. The exact consequences after using titania as support could not make out from the XRD and Raman measurements. The XPS measurements indicated that the Ce and La present in 3+, 4+ and 3+ oxidation states, respectively. The HREM results ascertained the formation of nanometer sized mixed oxides of Ce-La, whose grain size does not increase above 9 nm upon increasing the calcination temperature from 773 to 1073 K. Information about the lowering of symmetry and consequent strain development at the cerium sites could be obtained from the UV-vis DRS measurements. The TPR analysis shows the high reducibility of the system and even after severe heat treatment the redox property remains intact. The OSC as well as the CO oxidation activity of the resultant system is found to be quite remarkable. More details pertaining to this interesting catalytic system are presented in this chapter.

Chapter 5 deals with structural and redox characteristics of $\text{CeO}_2\text{-La}_2\text{O}_3/\text{Al}_2\text{O}_3$ samples and their evaluation for OSC and CO oxidation activity. The $\text{CeO}_2\text{-La}_2\text{O}_3/\text{Al}_2\text{O}_3$ composite oxide (8:2:10 mole ratio based on oxides) was obtained by a deposition coprecipitation method. The addition of alumina resulted into remarkable stabilization of $\text{Ce}_{0.8}\text{La}_{0.2}\text{O}_{2-\delta}$ nano-crystals against thermal sintering at higher temperatures. Alumina remains as an inert carrier and does not form any unfavourable inert compounds with ceria. The XRD analysis of the sample calcined at 773 K revealed the presence of a cubic phase with the composition $\text{Ce}_{0.8}\text{La}_{0.2}\text{O}_{2-\delta}$. There is no evidence for phase segregation up to the calcination temperature of 1073 K. The presence of oxygen vacancies leading to the defective structure formation is revealed by Raman spectroscopic analysis. Both Ce and La present in 3+, 4+ and 3+ oxidation states, respectively as revealed by the XPS measurements. The TEM-HREM results ascertained the formation of nanometer sized mixed oxides of Ce-La. The grain size does not increase above 7 nm upon increasing the calcination temperature from 773 to 1073 K. The UV-vis DRS measurements disclose information about the lowering of symmetry and consequent strain development at the cerium sites. The TPR analysis shows that the reduction temperature of the system is substantially low and no significant decrease is observed even after severe heat treatment. The OSC as well as the CO oxidation activity of the resultant system is found to be quite remarkable. More details pertaining to this interesting catalytic system are presented in this chapter.

Chapter 6 deals with the preparation and physicochemical characterization of $\text{CeO}_2\text{-La}_2\text{O}_3/\text{SiO}_2$ catalysts by various spectroscopic and non-spectroscopic techniques and their evaluation for OSC and CO oxidation activity. The $\text{CeO}_2\text{-La}_2\text{O}_3/\text{SiO}_2$ (8:2:10 mole ratio based on oxides) was obtained by an aqueous deposition coprecipitation method. These samples were subjected to various thermal treatments. The addition of silica remarkably enhances the surface area of the final catalyst. The XRD results suggest that the $\text{CeO}_2\text{-La}_2\text{O}_3/\text{SiO}_2$ sample primarily consists of nanocrystalline cubic Ce-La oxides with composition $\text{Ce}_{0.8}\text{La}_{0.2}\text{O}_{2-\delta}$ over the amorphous SiO_2 surface at all the calcination temperatures investigated. However, the peak widths of the nanosized materials are so large that it is not easy to draw an exact statement whether small amounts of segregated phases are present or not. The Raman measurements also revealed the existence of cubic ceria-lanthana phase and indicated the formation of oxygen vacancies as a result of lattice defects formation. The XPS patterns indicated that the Ce and La present in 3+, 4+ and 3+ oxidation states, respectively. The TEM-HREM results pertaining to $\text{CeO}_2\text{-La}_2\text{O}_3/\text{SiO}_2$ indicated well-dispersed Ce-La oxide nanocrystals (~6 nm) over the surface of amorphous SiO_2 matrix when treated at 773 K, and there was no apparent increase in the crystallite size upon subjecting to 1073 K. The experimental images revealed that the Ce-La oxides are mainly in the cubic geometry and exhibit high thermal stability. The UV-vis DRS measurements disclose information about $\text{Ce}^{4+} \leftarrow \text{O}^{2-}$ and $\text{Ce}^{3+} \leftarrow \text{O}^{2-}$ charge transfer transitions. The TPR analyses indicated the interesting redox property of the catalyst system. The reaction studied was selective dehydration of 4-methylpentan-2-ol, which is used as a test reaction to evaluate the acid-base character of oxide catalysts. Among all the catalysts silica supported ceria-lanthana system showed highest activity toward the dehydration of the 4-methylpentan-2-ol selectively.

On the whole, using soft chemical routes nanometer sized ceria-lanthana and different supported ceria-lanthana mixed oxide solid solutions could be successfully synthesized. Physicochemical characterization of all the catalyst systems showed that the systems are thermally quite stable, and possess very high surface area. Remarkable redox property was disclosed by the catalysts even after severe heat treatment. The oxygen storage capacity of all the systems is substantially high, titania supported ceria-lanthana and silica supported ceria-lanthana systems being the best towards the CO oxidation and dehydration of alcohols, respectively. Accordingly, these systems have shown the best catalytic activities for CO oxidation and dehydration of alcohols among the investigated systems.

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THESIS RELATED PUBLICATIONS

1. B.M. Reddy, G. Thrimurthulu, **L. Katta**:
Catalytic Efficiency of $Ce_xM_{1-x}O_{2-\delta}$ (M = Zr, Hf, Tb and Pr) Nanosized Model Solid Solutions for CO Oxidation
Catalysis Letters 141 (2011) 572.
2. B.M. Reddy, **L. Katta**, G. Thrimurthulu:
Novel Nanocrystalline $Ce_{1-x}La_xO_{2-\delta}$ (x = 0.2) Solid Solutions: Structural Characteristics and Catalytic Performance
Chemistry of Materials 22 (2010) 467.
3. **L. Katta**, P. Sudarsanam, G. Thrimurthulu, B.M. Reddy:
Doped Nanosized Ceria Solid Solutions for Low Temperature Soot Oxidation: Zirconium versus Lanthanum Promoters
Applied Catalysis B: Environmental 101 (2010) 101.
4. B.M. Reddy, **L. Katta**, G. Thrimurthulu:
Novel Nanosized $Ce_xZr_{1-x}O_2$, $Ce_xHf_{1-x}O_2$ and $Ce_xTb_{1-x}O_{2-x}$ Solid Solutions: Structural Characteristics and Catalytic Performance
Catalysis Today (In Press).
5. **L. Katta**, G. Thrimurthulu, B.M. Reddy:
Novel Nanosized $Ce_{1-x}La_xO_{2-x}/Al_2O_3$ Solid Solutions: Structural Characteristics, Redox Properties, and Catalytic Performance
ACS Catalysis (Submitted).
6. B.M. Reddy, **L. Katta**, G. Thrimurthulu, W. Grunert, M. Muhler:
Novel Nanosized $Ce_{1-x}La_xO_{2-x}/TiO_2$ Solid Solutions: Interfacial Interaction Driven CO Oxidation Reaction
Chemistry of Materials (Submitted).

OTHER PUBLICATIONS

7. B.M. Reddy, G. K. Reddy, **L. Katta**:
Structural Characterization and Dehydration Activity of CeO₂-SiO₂ and CeO₂-ZrO₂ Mixed Oxides Prepared by a Rapid Microwave-Assisted Combustion Synthesis Method
Journal of Molecular Catalysis A: Chemical **319** (2010) **52**.
8. D. Das, G. Thrimurthulu, **L. Katta**, B.M. Reddy:
Microwave-Assisted Synthesis of Highly Active Nanosized Ceria-Zirconia Solid Solutions for CO Oxidation
International Journal of Nanotechnology **7** (2010) **1166**.
9. B.M. Reddy, G. Thrimurthulu, **L. Katta**, Y. Yamada, S.-E. Park:
Structural Characteristics and Catalytic Activity of Nanocrystalline Ceria-Praseodymia Solid Solutions
Journal of Physical Chemistry C **113** (2009) **15882**.
10. B.M. Reddy, P. Saikia, P. Bharali, **L. Katta**, G. Thrimurthulu:
Highly Dispersed Ceria and Ceria-Zirconia Nanocomposites over Silica Surface for Catalytic Applications
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11. B.M. Reddy, G. K. Reddy, K. N. Rao, **L. Katta**:
Influence of Alumina and Titania on the Structure and Catalytic Properties of Sulfated Zirconia: Bechmann Rearrangement
Journal of Molecular Catalysis A: Chemical **306** (2009) **62**.
12. B.M. Reddy, P. Bharali, G. Thrimurthulu, P. Saikia, **L. Katta**, S.-E. Park:
Catalytic Efficiency of Ceria-Zirconia and Ceria-Hafnia Nanocomposite Oxides for Soot Oxidation
Catalysis Letters **126** (2008) **125**.

SYMPOSIA/ CONFERENCE/ PRESENTATIONS

1. **K. Lakshmi**, G. Thrimurthulu, P. Sudarsanam, B.M.Reddy:
Novel nanosized ceria-based solid solutions: characterization and catalytic evaluation towards CO and soot oxidation.
20th National Symposium on Catalysis (NSC-2010), IIT Chennai, 19th – 22nd December, 2010 (Catalysis Society of India).
2. G. Thrimurthulu, G. Raju, B. A. Dar, **L. Katta**, B. M. Reddy:
Structural characterization and CO and soot oxidation activity of novel nanocrystalline Ce_{1-x}M_xO₂ (M = Pr, and Zr) solid solutions.
New Dimensions in Chemical Sciences, Hyderabad, 2010 (University College of Science, Saifabad, Osmania University, Hyderabad)
3. **K. Lakshmi**, G. Thrimurthulu, D. Das, P. Sudarsanam, B. M. Reddy:
Design of novel nanocrystalline ceria-banded mixed oxides for catalytic applications.
(Awarded best poster)
12th CRSI National Symposium in chemistry, Hyderabad, 2010 (Indian Institute of Chemical Technology, Hyderabad)
4. **K. Lakshmi**, P. Saikia, P. Bharali, G. Thrimurthulu, B. M. Reddy:
A comparative study on catalytic behavior of Al₂O₃ supported nanostructured ceria-based mixed oxides. **(Awarded best poster)**
National Conference in Recent Advances on Chemical Research, Hyderabad, 2009 (University College of Science, Osmania University, Hyderabad).
5. G. Thrimurthulu, G. Raju, B. A. Dar, **L. Katta**, B. M. Reddy:
Influence of reducible and non-reducible dopants on the properties of ceria: Novel nanocrystalline Ce_{1-x}M_xO₂ (M = Pr, and Zr) composite oxides for catalytic applications.
(Awarded best poster)
National Workshop on Catalysis: Catalysis for Clean Environment and Sustainable Future, Tezpur, 21st– 23rd December, 2009 (Catalysis Society of India). (University of Tezpur, Tezpur).
6. **L. Katta**, P. Saikia, P. Bharali, G. Thrimurthulu, B.M. Reddy:
A comparative study on catalytic behaviour of Al₂O₃ supported nanostructured ceria-based composite oxides
CATSYMP-19: Catalysis for Sustainable Energy and Chemicals, Pune, 18th – 21st January, 2009 (Catalysis Society of India).
7. P. Saikia, P. Bharali, G. Thrimurthulu, **L. Katta**, B.M. Reddy:
Doping of different isovalent cations (Hf⁴⁺, Zr⁴⁺ and Tb⁴⁺) into ceria and their influence on OSC and CO oxidation activity. **(Awarded best poster)**
National Workshop on Catalysis: Futuristic Materials as Catalysts and Adsorbents, Bhubaneswar, 18th– 20th February, 2008 (Catalysis Society of India).

8. **L. Katta**, G. Thrimurthulu, P. Saikia, P. Bharali, B.M. Reddy:

Influence of isovalent cations on OSC and CO oxidation activity of cerium oxide.

National Symposium on Chemistry-Technology Interface: A Synergistic Approach, Hyderabad, 30th September – 2nd October, 2007 (Department of Chemistry, Nizam College, Osmania University)

AWARDS AND HONOURS

1. During Ph.D, visited Ruhr University of Bochum, Germany under DST-DAAD project based personal exchange programme for two months in the year **2010**.
2. Awarded **BEST POSTER** for the poster “Design of novel nanocrystalline ceria-based mixed oxides for catalytic applications” by **K. Lakshmi**, G. Thrimurthulu, D. Das, P. Sudarsanam, and B. M. Reddy presented at *12Th CRSI National Symposium in chemistry, Hyderabad, 2010 (Indian Institute of Chemical Technology, Hyderabad)*.
3. Awarded **BEST POSTER** for the poster “Influence of reducible and non-reducible dopants on the properties of ceria: Novel nanocrystalline $Ce_{1-x}M_xO_2$ (M = Pr, and Zr) composite oxides for catalytic applications” by G. Thrimurthulu, G. Raju, B. A. Dar, L. Katta, and B. M. Reddy at National Workshop on Catalysis: Catalysis for Clean Environment and Sustainable Future, Tezpur, 21st – 23rd December, **2009** (Catalysis Society of India) (University of Tezpur, Tezpur)
4. Awarded **BEST POSTER** for the poster “A comparative study on catalytic behavior of Al_2O_3 supported nanostructured ceria-based mixed oxides” by **K. Lakshmi**, P. Bharali, P. Saikia, G. Thrimurthulu., B. M. Reddy presented at *National Conference in Recent Advances on Chemical Research, Hyderabad, 2009 (University College of Science, Osmania University, Hyderabad)*.
5. Awarded **BEST POSTER** for the poster “Doping of different isovalent cations (Hf^{4+} , and Tb^{4+}) into ceria and their influence on OSC and CO oxidation activity” by P. Saikia, P. Bharali, G. Thrimurthulu, **L. Katta**, B.M. Reddy presented at *National Workshop on Catalysis: Futuristic Materials as Catalysts and Adsorbents, Bhubaneswar, 18th – 20th February, 2008 (Catalysis Society of India)*.
6. Participated in the “Orientation programme for research scholars in catalysis” at the *National Centre for Catalysis Research, Department of chemistry, Indian Institute of Technology, Madras, 17th Nov – 7th Dec, 2007*.
7. Qualified Joint CSIR-UGC National Eligibility Test (NET) as CSIR JRF–**2006**.
8. Qualified Graduate Aptitude Test for Engineering (GATE) -150 Rank –**2006**.
9. Qualified Bhabha Atomic Research Centre (BARC) –**2006**.